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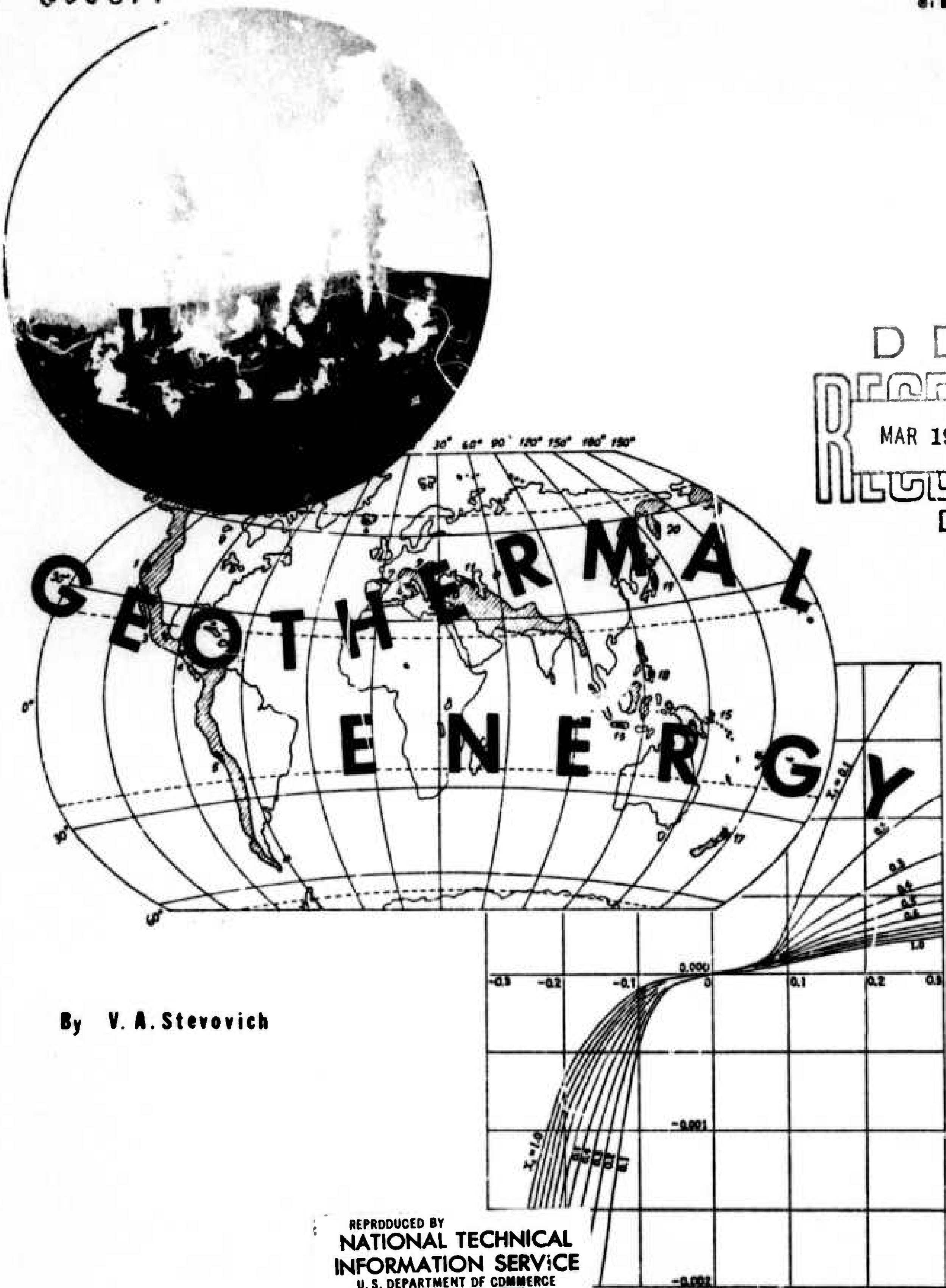
GEOTHERMAL ENERGY



By V. A. Stevovich

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This is a comprehensive review of present major developments and future planning in various fields of applied geothermal engineering. The study covers theoretical and experimental data on the background and state-of-the-art of applied geothermal research in general, with emphasis on foreign work.

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INTRODUCTION

This report is a comprehensive review of major research and development and future planning in various fields of geothermal engineering. In general, the study covers theoretical and experimental data on the background and state-of-the-art of applied geothermal research with emphasis on foreign activities.

Exploration for geothermal energy and its subsequent exploitation, calls for the coordinated efforts of a team of specialists versed in different disciplines. Each specialist can gain a better persepective of his function in such teamwork if he has at least some understanding of the problems and techniques of his collaborators. This study should also enable the nonspecialized reader to obtain a broad idea of geothermal energy in general and of its associated specializations in particular.

Those readers who become more interested in the subject of an article or wish to pursue their quest for more information are referred to the extensive reference list, so that the reader's study may be guided and extended as far as desired.

Even today, there are people who are under the impression that there is something unusual and impracticable about geothermal energy. This review attempts to correct that impression and persuade the reader that the economic exploitation of geothermal energy is one of the established facts of life. The extensive reference list indicates a broad spectrum of knowledge, experience, growing interest, and viewpoints on various aspects of geothermal engineering for industrial and domestic purposes.

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I. GENERAL ASPECTS OF GEOTHERMY AND GEOTHERMAL ENGINEERING

A. General

Natural surface manifestations of geothermal energy, such as hot pools, steam vents, geysers, mud volcanos, and mineral-thermal springs, have been known for a long time, but the broader significance of their economic potential has come under consideration only in recent years [1].

Not so long ago, the geothermal energy was regarded as an interesting freak of nature and as such a tourist attraction in the form of geysers, fumaroles and pools of boiling mud. Its practical side was then more or less confined to its alleged curing properties for various human ailments.

It is known fact, that nether regions of the earth are very hot, but in most parts of the world the observed temperature gradients in the outer crust average only about one degree centigrade for every hundred feet of depth. In certain regions much steeper temperature gradients occur, sometimes as much as a hundred times the normal. The heat in these regions is termed geothermal energy. Such thermal regions are usually, but not always, closely associated with volcanic activites and earthquakes. The majority of these earthquakes occur in clearly defined belts or zones mostly of comparatively narrow width. The most important of these earthquake zones, which also contain a great number of active and extinct volcanos, more or less follow the periphery of the Pacific Ocean. Another important zone runs along the middle of the Atlantic Ocean with an easterly branch passing through the Mediterranean and Middle East into Tibet [2].

However, economically significant concentrations of geothermal energy occur in local "hot spots" where high temperatures (70 to 340°C) are found in porous rock containing water or steam. Such concentrations of extractable heat are known as geothermal reservoirs and are found either

in regions of recent volcanism or in the deep areas of sedimentary basins. Based on geological exploration, the entire circum-Pacific belt, the African Rift System, the Lesser Antilles, the Italian-Aegean belt, and the Red Sea are areas of great geothermal significance. All these zones are interconnected, except for a small isolated zone centered on the Hawaiian Islands. There appears to be an interrelation between the chemistry of lava erupted in these zones and the frequency of areas with geothermal activities. Most, if not all, high temperature areas show a close connection with eruptive centers that have produced silicic lava or tephra in great amounts. However, manifestations of geothermal anomalies through natural fissures of permeable volcanic rock are noted at much shallower depths with temperature of 300°C at a few decimeters depth, and far higher temperatures (up to about 700°C) have been recorded in shallow holes drilled to depths of 27 meters [5].

Geothermal areas generally tend to lie within earthquake belts, though not necessarily close to volcanos. For example, Larderello in Italy and The Geysers in California, two of the most famous geothermal fields, lie at a considerable distance from the nearest volcanos. Thermal areas are also known outside the earthquake zones, such as in Kenya, Hungary and various parts of the Soviet Union.

Various theories and models have been advanced to account for the origin of geothermal heat and the mechanism of its convection. The actual source of the heat is now almost universally believed to be radioactivity, mostly within the crustal rocks, while the theory of continental drift offers an interesting and plausible explanation of the broad confinement of earthquakes to certain clearly observable zones. In these zones, crustal weaknesses enable deep-seated heat to rise nearer to the surface of the earth [2].

In general, lower enthalpy fluids are far more abundant in volcanic zones and elsewhere, and may represent a greater reserve of useful energy. Significant areas of low enthalpy fluids include the Gulf Coast of the United States, an extensive region in western Siberia, and portions of central Europe just north of the Alps and the Carpathian Mountains. Geologically,

these are subsiding sedimentary basins at the margins of folded mountain ranges. Water encountered during exploration for oil in sedimentary basins has usually been considered a nuisance. But in the future these hot waters of relatively low enthalpy may represent an energy source as valuable as oil. Other low enthalpy waters have been encountered in wells and mines or as occasional warm springs in older folded mountains, but rarely in the ancient stable platforms and shields of continental interiors [10].

1. Historic background

For several thousand years man has known of the existance of geothermal energy, and ancient man was familiar with volcanos, geysers and warm springs [6]. In ancient times the Romans, and in modern times the Icelanders, Japanese, Turks and others have used it for baths and space heating. At Larderello in Tuscany the Italians have been extracting boric acid from steam jets since the 18th century and it was here that electric power was first successfully generated from geothermal heat. Even before the turn of the present century attempts were being made to use reciprocating engines supplied with raw natural steam. Now, a group of power stations in the Larderello district are collectively generating over 300 MW [2].

For more than a century, wells have been drilled to produce petroleum, but geothermal energy has been tapped on a moderate scale only during the last 20 years, except in Italy where the economic potential of this energy was recognized with the first steam well drilled at Larderello in 1904 [1]. New Zealand was the second country to capitalize on geothermal resources, and it already has a capacity of about 200 MW of electric power. Domestic and industrial heating by geothermal heat was initiated in Iceland in 1925, and over 100,000 residents now live in houses heated in this manner.

Based on encouraging progress in these countries, exploration and development programs were initiated in Burma, Chile, Colombia, El Salvador, Ethiopia, Guatemala, Japan, Kenya, Mexico, Nicaragua, Turkey, the Soviet Union, and the United States. With growing interest in this

natural source of energy many more countries have become active or are expected to conduct various exploratory works in the near future [3]. The Resources and Transport Division of the United Nations has given technical assistance on geothermal development to about nineteen countries, while the United Nations Development Program has in hand through its Special Fund, five geothermal exploration projects in Turkey, El Salvador, Chile, Kenya and Ethiopia. A request for a similar project has been submitted by the Government of the Philippines, and several other countries are examining the possibilities of geothermal development.

In spite of the cheapness of exploited geothermal resources, it appears that development has been slow and that many geothermal fields are still neglected. The basic reason for this is financial risk, since all geothermal fields do not readily yield to economic exploitation. To determine whether a field can be profitable it is necessary to expend fairly large sums in exploration. If the results are positive, exploration costs will be well justified, otherwise they will be largely wasted except in the interest of pure science.

Therefore, the cost of geothermal exploration may be regarded as risk capital, such as that associated with petroleum exploration. It is in this respect that the United Nations Development Program has rendered great assistance. Its Special Fund activities are specifically designed to undertake preinvestment responsibility and to relieve the client government of some of the risks which they cannot afford. The five geothermal exploration projects mentioned earlier are examples of such work undertaken by the United Nations Development Program. However, some of the more developed countries have felt confident enough to undertake their own geothermal exploration without the help of any international organization, including Italy, New Zealand, Iceland, Japan, Mexico, Soviet Union, and the United States [2].

2. The role of geology, hydrology and hydrogeology

Geology and hydrology have considerable roles in the exploration of geothermal sources. In particular, geology is interrelated to the more

specialized disciplines of geochemistry and geophysics. In contrast with geochemistry and geophysics, which use well-defined techniques of data collection and standardized methods of interpretation, geology is more of a subjective discipline in which conclusions are based on a minimum of information that is often internally inconsistent. The objective of geothermal exploration is to find a reservoir of thermal fluid of sufficiently high temperature and permeability to produce economic quantities of heat and/or fluid to justify economic exploitation. The role of the geologist is to minimize exploration risk by ensuring that:

- the region selected for initial reconnaissance is likely to contain good prospecting areas for detailed exploration;

- appropriate geology, hydrology, hydrogeology, geochemical and geophysical data are collected and interpreted in order to select the most promising prospecting areas and the best possible locations for exploratory drill sites;

- assuming a discovery is made, ensuring the collection of all appropriate well data in order to determine the reservoir parameters.

Thus the geologist must be familiar with a great variety of specialized exploration, drilling and well-testing techniques to ensure their proper coordination in the overall exploration effort.

In selecting a region for preliminary reconnaissance, the best and most obvious criterion is the presence of thermal manifestations.

In order to assess the potential of various geologic environments for the production of geothermal resources, it is necessary to examine in some detail the environments of known geothermal systems. The general relationship of such systems to young orogenic zones, and in particular to recent volcanism within these zones, is well known. When examined in detail, however, this relationship is found to be far from simple. Some orogenic zones, particularly the island arcs, are intensely volcanic and contain a high density of high

temperature manifestations. Other young orogenic zones, on the other hand, contain few volcanic centers and have a low density of low temperature springs. Examples of this type of orogen are the Alps, Taurus, Outer Carpathians, Southern Atlas, and the Eastern half of the North American Cordillera. There are regions having moderate to high temperature springs with no associated young volcanism, such as Central Anatolia and the Basin and Range Province of Western North America. Furthermore, there are young volcanic zones, such as the Cascade Range and the Hawaiian islands, which have very few hot springs. Needless to say, the general relationship between orogenic zones, volcanic centers, and thermal systems will require a great deal of investigation before it is thoroughly understood. However, new relevant information has been brought to light during the last decade.

Of the 43 geothermal fields proved by drilling, 27 (63%) are associated with Quaternary volcanic centers. Of these, 11 are in structures related to volcanic processes, such as calderas and fractures peripheral to volcanic domes (e.g. Matsukawa and Otake, Japan; Matsa, Taiwan; Ahuachapan, El Salvador; and the Monte Amiata fields, Italy). The remaining 16 fields associated with Quaternary volcanic centers occur in fault block structures related to tectonic rather than volcanic processes (e.g. Wairakei and Broadlands, New Zealand; the Geysers and Salton Sea, U.S.A.; and Cerro Prieto, Mexico). The reservoir temperatures of the first group average about 220°C and of the second group about 250°C. These temperatures are usually found at depths of 500 to 1,000 m.

Ten of the 43 fields proved by drilling (23%) have been found in areas unassociated with Quaternary volcanism. Of these, 5 are in hinderland fault block structures (e.g. Larderello, Italy; and Kizildere, Turkey); 3 in hinterland basins (e.g. the Hungarian Basin; and the inter-mountain basin of Georgia, U.S.S.R.); and 2 in rift zones (in Iceland). In the depth range of 500 to 1,000 m, the reservoir temperatures of the first group average 190°C, the second 85°C and the third 120°C.

The remaining 6 of the 43 fields are located outside tectonic zones in foreland and platform areas, such as the Pre-Caucasus foreland and the West Siberia platform of the U.S.S.R. Unlike the fields discussed above, reservoirs in foreland and platform areas are not hyperthermal, but rather their temperatures reflect the world average gradient of approximately 30°C/km of depth. From depths of about 2,000 m, however, reservoirs found in this environment are capable of producing considerable quantities of 60 to 100°C water suitable for large scale industrial use or domestic heating.

The following table summarizes this information and shows probable average temperatures to be expected in geothermal systems at 500 to 1,000 m depth in various geologic environments.

Geologic environment	Average reservoir temperature to be expected, °C
Fault block terrains associated with Quaternary volcanism	250
Volcanic structures associated with Quaternary volcanism	220
Fault block terrains in Cenozoic hinter-land regions, without Quaternary volcanism	190
Cenozoic Rift zones, without Quaternary volcanism	120
Sedimentary basins in Cenozoic hinter-lands, without Quaternary volcanism	85
Foreland and platform regions, without Quaternary volcanism	30

No absolute economic limit can be placed on the minimum usable temperature for a geothermal fluid, because this will depend on the use to which it is put and will vary from place to place according to the competitive cost of other local sources of energy. At the present level of technology, however, a minimum temperature of about 180°C is required for power generation, although lower temperatures may be used for many industrial

processes or for domestic heating. As power is the primary application of goethermal resources, the geology of only the first three environments listed in the above table will here be emphasized.

Most tectonic zones have a distinct structural asymmetry imposed by the horizontal component of the stresses causing the deformation. The direction of the horizontal component of movement is reflected in the geometry of the deformed rocks, the asymmetry being most commonly seen in the preferred direction of overturning of folds and of thrusting. The region towards which the folds are inclined and the thrust directed is called the foreland, and the region away from which these structural elements are directed is called the hinterland. Hinterland regions are generally characterised by high heat flow, numerous hot springs and, in some cases, by widespread volcanic activity: it is in these regions, rather than the folded and thrusted zones, or the foreland regions, that high temperature geothermal fields are generally found.

In contrast to the folded and thrusted zones, hinterland regions are characterised by normal faulting which gives rise to fault block terrains. Geothermal systems appear to be genetically related to the normal fault zones in two ways:

- Normal faulting indicates tectonic extension of the crust which in turn may promote the intrusion of magma bodies close to the surface through some mechanism such as the release of confining pressure on rock already close to its melting point, and/or the provision of steeply dipping and deep penetrating fault zones up which the magma can rise;

- The faults also provide steeply dipping permeable channels through which surface water can circulate to considerable depth, become heated, and return rapidly to the surface.

Normal faulting does not give rise to a random series of horsts[1] and grabens[2], as commonly implied in general descriptions of these regions. The characteristic structural form resulting from the faulting is a series of tilted fault blocks. Belts of tilted fault blocks complement the asymmetry of adjacent folded and thrusted zones, where present. In the vertical plane, the asymmetry is expressed by the blocks being tilted in one dominant direction corresponding to the direction of tectonic movement in the adjacent folded and thrusted zone. In the horizontal plane, the asymmetry is expressed by arcing of the fault traces, the convex side of the arcs being dominantly oriented towards the direction of tectonic movement in the adjacent folded and thrusted zone.

Individual faults can be traced for several tens of kilometers over which distance their strike may swing through 10 to 30 degrees of arc. The concave side of the arc is consistently on the down-thrown side of the fault.

The throw of the fault, at least as measured on the surface, complements the degree of tilting of the associated fault block, that is, Quaternary strata may be offset only a few tens of meters and tilted only a few degrees; while Mesozoic formations may have stratigraphic offsets of several thousands of meters and tilts of 40 to 60 degrees. The width of individual fault blocks, measured perpendicular to strike, ranges from about 2 km to several tens of kilometers, as in the African Rift zones, or many hundreds of kilometers as in the Basin and Range Province of the North American Cordillera.

The convex side of the fault belt, i.e. the side towards which the blocks are dominantly tilted, is here termed the frontal border of the belt, on which the belt can be terminated by:

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1) Horst is a longitudinal up-faulted block formed by complex stress in the earth's crust.

2) Graben is a longitudinal down-faulted block formed by complex stress in the earth's crust.

- a folded and thrusted zone, with the direction of axial plane tilting and fault thrusting corresponding to the direction of arcing and fault block tilting in the adjacent normal faulted zone. Examples of such terminations exist in various parts of the North American Cordillera from Western Canada southward through Idaho to Wyoming;

- a monocline that dips into a major structural depression, the monocline having the same direction of dip as the adjacent tilted fault blocks. Examples include El Salvador, where the monocline dips southward beneath the Pacific Ocean and appears to form the north flank of the Central American Trench; and northern California where the monocline forming the east side of the North Coast Ranges dips eastward into the Central Valley;

- a gently tilted plateau, again tilted in the direction of arcing and tilting in the adjacent fault belt. This type of termination is characteristics of the East African Rift zones, but is also found in North American (The Colorado Plateau) and in New Zealand (The Kaingaroa Plateau).

In contrast with vapor dominated systems, hydrostatic pressure is available in hot water systems and consequently, high temperatures can be attained without the necessity of a tight cap. If the top of such a system can reach the surface relatively unaffected by near-surface lithologic or hydrologic barriers, its surface heat discharge can be taken as an order of magnitude indication of the amount of energy that could be produced by drilling; and the extent in area of the manifestations, which would consist mainly of boiling springs, would be a fair indication of the area of productive ground. The Wairakei and Yellowstone thermal areas appear to be of this type. These systems, however, are in some ways unique. Many hot water systems, are prevented from discharging directly to the surface by a variety of geologic and hydrologic circumstances.

Impermeable lithologic horizons can confine the top of a thermal system and deflect the up-flowing water many kilometers laterally. The closest point at which water discharges from the Ahuachapan thermal system,

for example, is 7 km away from what is believed to be the center of the up-flow. The water is marked at the surface only by steam-heated shallow groundwater. Loss of heat by boiling, and perhaps dilution with cold groundwater, lowers the temperature of the thermal fluid from 230°C near the center of the system to 70°C at the closest discharge point.

A type of lithologic barrier quite commonly found over the top of thermal systems consists of fine lake or stream sediments deposited in the fault angle formed between tilted fault blocks. Some, or perhaps most, of the thermal fluid rising along the fault can be deflected by the impermeable sediments and travel up-dip beneath them to the opposite side of the lake basin or alluvial valley. At the Kizildere field in Turkey, thermal fluid is deflected about 5 km from the center of up-flow by this type of geologic condition. Where springs occur at the contact of alluvium with bedrock, rather than on fault or fracture zones, deflection of this kind should be suspected.

Lithologic barriers are not the only features to prevent thermal systems from discharging directly to the surface. Local hydrologic conditions can also be a controlling factor. If, for example, the top of the thermal system is intersected by a large confined cold water aquifer, the heat will be swept down-gradient; and either it will be dispersed so that no evidence of the system ever appears at the surface, or the aquifer fluid may discharge at the surface as large-volume warm springs many kilometers distant from the actual source of heat. The correct interpretation of these large-discharge warm springs is difficult because they can be caused either by a remote, but localised, high temperature source, or be due to only a high conductive heat gradient extending over a large region.

Another type of hydrologic condition which greatly modifies the surface expression of a thermal system is where the top of the system intersects an unconfined, but quite deep groundwater body. If the groundwater is stagnant, or moving slowly, and the input of heat from the thermal system is sufficient to cause the groundwater to boil, surface manifestations will consist of patches of gently steaming ground unassociated with high pressure fumaroles at temperatures above the atmospheric boiling point. If the depth to the water

table is great, of the order of 300 m or more, much of the rising steam will be condensed in the unsaturated zone and thus the amount of heat will be considereably less than that available at depth.

It will thus be appreciated that in order to use surface heat flow as a reliable criterion for selecting promising thermal systems for detailed exploration, it is first necessary correctly to interpret the local geologic and hydrologic conditions modifying the surface expression of the system [4].

The testing of geothermal fields is a methodologically new department in the practice of hydrogeological surveying, a department that only originated in recent years. Methods for testing geothermal wells developed by the Pauzhetka Observation Station of the USSR Academy of Sciences in Kamchatka are based on hydrogeological studies, which provide the most reliable approach to the study of hydrothermal fields. Since the thermal water tapped by the well at depth is in the liquid phase, its dynamics is governed by fundamental hydrogeological laws, permitting the use of the formulas of underground hydraulics in the calculations. In general, high temperature creates considerable difficulty in the dynamics of geothermal wells. In operating wells, steam generation is at great depth, resulting in the formation of a vapor lift, and assuring a high yield for the well. Consequently, in evaluating the hydrodynamic conditions of the well, analysis of the thermophysical data is of particular importance. The process of differentiation in the chemical composition of the geothermal water tapped by a well is closely associated with the specific features of the dynamics. During ebullition, the volatile substances are readily transferred from the water phase to the steam phase, while the concentration of most salts in the water increases. To obtain a correct idea of the composition of the steam-water mixture, one must know the composition of the steam phase and the water at the point of discharge, as well as the water-steam ratio.

To formulate complete hydrogeological and energetic characteristics of a geothermal field, the following are the principal data required:

Thermophysical data: water and rock temperatures in a steady-state well; enthalpy of the steam-water mixture at discharge; and steam pressure at the wellhead.

Hydrodynamic data: position of the static level of the thermal water; rate of flow of the steam-water mixture at varying steam pressures at the wellhead; and position of steam-generation levels at varying flow rates.

Chemical data: chemical composition of water; chemical composition of steam; and weight ratio of water to steam in drawing samples for analysis.

Analysis of the above basic data permits evaluation of the energy capacity of the well, selection of the most practical regime of operation for it, and establishment of the hydrogeological conditions prevailing at the site of the well [9].

3. Characteristics of geothermal systems

The source of water and the nature of geological formations consititute a basis for determining the location and type of geothermal systems, which can be categorized as either an "open system" or a "buried system". The open systems are fed from the surface and are open throughout their extent [29]. Some manifestations observed at several volcanos in the more elevated areas of Kamchatka are related to these types. The buried systems are those which utilize fossil waters or waters released by sediments under geostatic pressure. A similar situation is verified in the Caucasus where attempts have been made to utilize depleted oil deposit sites by injecting water into selected wells and extracting hot water from adjacent wells. Presently, such water is being used for industrial and agricultural purposes [28].

The basic features of a geothermal steam field, wet or dry, are shown in Fig. 1. These features are: a source of natural heat of great output; an adequate water supply; and aquifer, or permeable reservoir rock, and a cap rock.

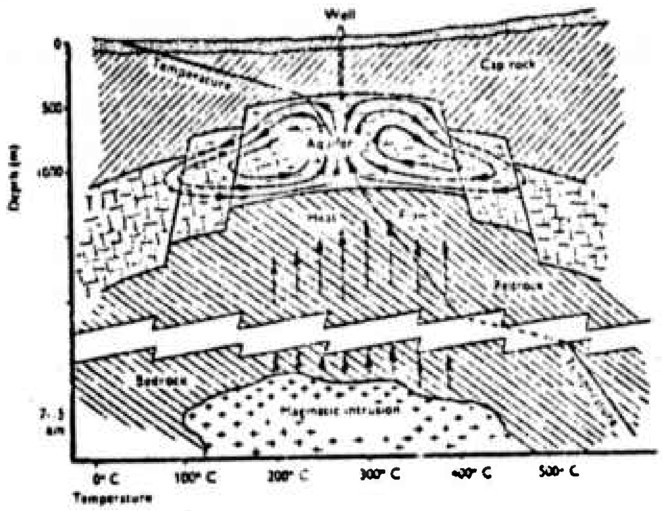

Fig. 1. Basic model of a steam field [12].

<u>The source of heat</u> is a magnetic intrusion into the earth's crust, having a temperature of 600 to 900°C, often at depths ranging between 7 and 15 kilometers. This view is supported by various facts and accounts for the reason that all known commercial fields are in regions where volcanic activity has occurred during recent Miocene-Quaternary times, or is still occurring. Some fields are actually situated on, or are close to volcanos (e.g. Japan and Central Mexico), whereas other (Larderello, Italy) are not directly linked with a center of recent volcanic activity. However, Larderello is located within the northern part of the large Tyrrhenian volcanic province; steam fields thus appear to be located in areas either of active or of dormant volcanism.

In an active volcano, a magmatic intrusion reaches the surface through a large fault system. In compact, hard rock faulting may provide a channel for the upward flow of magma, while plastic rocks such as clay may flow by gravity into the fault space and seal it from above. The energy of a magmatic intrusion may be sufficient to penetrate the fault system in hard rocks but insufficient to prevail against the overburden of the plastic rocks. In such cases the magma may intrude to the boundary between the hard and plastic rocks. This cryptovolcanism may occur in areas devoid of recent volcanic activity, and is more likely to be found in geological areas of thick

plastic formations, like a turbiditic series (flysch, greywacke). This applies to the two major dry steam fields, Larderello and the Geysers.

Magmatic intrusions without present eruption are common in acidic volcanos and can also occur in basic volcanos. Such intrusions provide the heat source for the Japanese and Central Mexican fields located on or around volcanos.

Surface volcanic products like lavas, ignimbrites and tuffs cool too quickly to orignate a commercial geothermal field. Magmatic intrustions alone, that have occurred within the last half million years or so, can satisfactorily account for the heat source: older intrusions would probably have cooled off by now. The problem is how to find evidence of recent magmatic intrusions, some of which may be very deep seated.

The water supply. Early hypotheses about geothermal fluids suggested that they were of magmatic, or juvenile origin, that is, water vapor and gases released from solution in the magma when the pressure is reduced. This may still be partially true, but it is now believed that at least 90 percent of the water in a geothermal reservoir is meteoric, originating from rain water. Geochemical evidence based on isotopic measurements support this opinion. Thus, referring to Fig. 1, it would appear that most of the water in the aquifer is of meteoric origin and that it is heated conductively through a large impermeable base rock, even though a relatively small quantity of magmatic steam may penetrate this base rock through faults and fissures.

As hot fluid is withdrawn from bores or from surface vents, the hydrological balance of the system is restored, or partially restored, by the inflow of new water. There are often clearly visible recharge areas, where the permeable reservoir terrain outcrops, permitting the ingress of rainwater. At Larderello there are outcrops of the Mesozoic carbonatic and evaporitic series. Here it is possible to calculate from observed rainfall and runoff the quantity of meteoric water entering the reservoir each year. In other geothermal fields matters are not always as simple. Many

hydrothermal systems are dynamic, with water entering at some high level and leaving at some low level. Our knowledge of water movement in deep aquifers is very limited, especially where these lie below sea level, as is so often the case [12].

Although quite complex, the hydrogeological conditions in the Georgian SSR come within the scheme of ground hydrology. Water circulation in some cases is at relatively deep horizons where the heat flow varies from moderate values for the Georgian Block (0.68-1.22 microcal/cm^3sec) to rather high values in the Adzhar region (1.49-2.03 microcal/cm^3sec) [47]. However, considering the situation in Kamchatka as a whole, and the Pauzhetka system in particular, there are indications that the cold, thermal, and hyperthermal waters are hydraulically interconnected. In consequence, the piezometric levels of the Kamchatka thermal waters, measured in wells of the region's geothermal system, agree with the static levels of the local cold waters [27]. This interference phenomenon between the cold descending flow and the hot portion of the system results in a general decrease in the temperature of the extracted fluids, and in an increase of water quantity drawn to the surface from the wells. Flashing occurs only near the well bottom or actually inside the well, thus creating scales which obstruct the fracture and reduce the diameter of the well. This causes considerable reductions in yield and in some cases, an actual stoppage.

In specific cases, there is the possibility that a geothermal system has an almost direct connection between the recharge and discharge areas. This opinion has been supported by a recent Soviet study [48] which has shed new light on the origins of geothermal water. Field data, collected over various areas on the chemical components, isotopes, and organic material in geothermal waters, including the hydrothermy of recent volcanism, indicate regional characteristics and continuity of such waters in the upper hydrogeosphere. The interpretation of the data obtained is based on geotectonic, lithologic-facial, geothermal, and geochemical characteristics

of the system under consideration. It is concluded that the basic sources of water, mineral salts, gases, and organic material in thermal waters are the result of atmospheric precipitation and filtered sea water.

Considerable attention is given to the condensation of steam in contact with the coldest levels of the reservoir top, particularly with those levels which correspond to the peripheral parts of the production areas. Regular observations conducted over many years on Kamchatka indicate that hydrothermal activitiy was unaffected by exploitation. However, a different picture is seen for the Pauzhetka wells where, through exploitation, a considerable decrease in the piezometric levels (and hence in hydrostatic pressure) has been observed. It is noteworthy that, during test drilling of the Pauzhetka deposit, a sharp decrease in piezometric level was accompanied by the transformation of a constantly boiling spring into a geyser with reduced output from 10.1/sec to 0.61/sec. With the termination of test drilling and the restoration of piezometric level, the former constant discharge was resumed. This transformation, involving hydrodynamic variations in the hydrothermal water system, shows conclusively that geysers and boiling springs share the same nature, and also that geysers are a special type of boiling spring. A decrease in hydrostatic pressure in areas with low piezometric level gives more intensive steam separation and thus more surface steam discharge [49]. This correlates with the fact that, at the Pauzhetka site, the surface thermal manifestations are not the result of changes in the temperature of the water-bearing complex. The above described examples demonstrate that geothermal systems must be classified and evaluated according to their types and potentials in order to predict the characteristics which they will display after a certain period of use. It is therefore important to broaden the base of experience and knowledge in forecasting the various modifications of a producing geothermal system and to predict the production time under varying conditions. Soviet scientists stress the great importance of models based on numerical, analog, or experimental methods, in the study of geothermal systems. Heat and mass transfer, important components of a hydrothermal system, are the bases of a Soviet attempt to create a mathematical model of a selected system.

Presently, the classifications of geothermal fields are based on chemical or thermodynamic criteria. There are proposals by several scientists that classification should be based also on geological criteria. However, some Soviet scientists differ with the present classification system of geothermal fields and suggest a dual classification of occurrence of thermal waters based on tectonic setting and type of heat source. Other proposals suggest the use of geological age, as well tectonic environment.

Based on the above classifications, Soviet scientists conclude that water having moderate to high thermal potential and in large quantities, can only be found in Cenozoic folded regions, in older regions reactivated in the Cenozoic age, and in the interiors of Paleozoic platforms. In addition, they distinguish between waters occurring in "fissure/veins" and those in permeable stratigraphic horizons called "stratal" deposits. The exploitable ratio is approximately 1 to 20, respectively [50]. Based on the above geological differences, the thermal gradient, depending on the tectonic structure of the region, varies from formation to formation. For example, in the western region of the Georgian SSR, the 50°C isotherm ranges in depth from 2000 meters near the Black Sea coast, and only 800 meters inland averages 1400 meters overall. This gives a maximum gradient of about 42° C/km, and an average gradient of only 21°C/km. In the eastern region of the Georgian SSR, the gradient ranges between 27 and 40°C/km. In general, the temperature gradients in these basins are from one and a half to two times the world average, making it possible to extract water at 80 to 100°C from relatively shallow depths over extensive areas. Geothermal fields found in platforms and foredeep areas are generally characterized by a normal heat flow, and they have geothermal gradients close to the world average [51].

The aquifer. A good productive geothermal well should produce at least 20 t/h of steam, and many wells produce a great deal more. A wet well may produce hundreds of tons per hour of mixed fluid. The maintenance of such high flow rates implies a high degree of permeability in the aquifer, with porosity playing only a secondary part. Any permeable rock can serve as a good geothermal reservoir. At the Geysers it is greywach with fissure permeability, and at Larderello a carbonate rock with karstic permeability. At Wairakei, New Zealand, fissured ignimbrite are overlaid with rhyolite

and pumice breccia; at Otake, Japan, with a permeable volcanic tuff, and at Cerro Prieto, Mexico, with deltaic sands.

A cap rock is a layer of rock of low permeability overlying the aquifer. All steam-producing fields have a cap rock. Some have been formed as original impervious rocks, such as the flysh formation at Larderello, the lacustrine formation at Wairakei, or the deltaic clay in the Imperial Valley and Cerro Prieto fields. Elsewhere, the cap rock may have become impervious as a direct result of thermal activity. For example, at the Geysers and at Otake, the shallow rocks are hard fractured formations. It is probable that before the beginning of thermal activity these rocks had a fissure permeability, and that this activity itself has caused the sealing of the permeable passages. This could have occurred by two geothermal processes: the deposition of minerals from solution, mainly silica, or through hydrothermal alteration of rock, causing kaolinization.

Deposition of silica can easily be observed in the Geysers field, where fractures of one-inch width, completely filled and sealed by silica and calcite, are common features. Kaolinization, associated with other more complicated hydrothermal rock alteration, is also widespread and prominent. Hydrothermal alteration can be recognized by the bleaching of greywacke, and in some places, by the lack of vegetation. Hydrothermal alteration is a very complex and not fully understood geochemical process that varies from place to place.

Sometimes a hot aquifer may insert in places within the cap rock. Where such zones have been exploited they were productive only for a limited time, and it was necessary to deepen the bores into the main convective reservoir.

A low temperature hot water field may sometimes occur in an environment similar to that shown in Fig. 1. It can also occur in fields devoid of cap rock, in which case the model is conceived somewhat in the

manner shown in Fig. 2, where the thermal gradient and depth of the previous aquifer are sufficient to maintain a convective circulation. The temperature in the upper part of the reservoir will not exceed the boiling point at atmospheric pressure, partly because water brought up convectively from depth will drop in pressure (and temperature) as it rises, and partly because there may be mixing with cold ground waters.

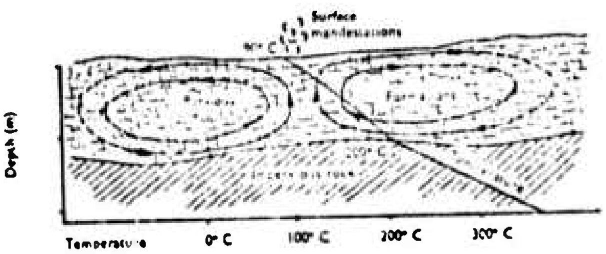

Fig. 2. Basic model of a low temperature hot water field [12].

If the permeability and depth of the aquifer are sufficient, and the supply of deep heat is also adequate, a convection system will be set up and maintained. Thus hotter water will be conveyed from the lower to the upper part of the aquifer and temperatures will tend to stabilize at or near the boiling point corresponding to the hydrostatic pressure, in the rising steam of the convective system which forms the active part of the field. However, temperature inversions are not uncommon, due to secondary disturbances in the convective system. A reservoir may be completely filled with water, often at or near boiling point corresponding to depth, or it may contain an upper layer of steam and gases.

When a bore is sunk into the water zone and fluid passes up it, flashing occurs due to the reduction of pressure. This flashing may occur in the well itself, at the walls of the well where water enters it, or within the reservoir at some distance from the well.

The location of the flashing point depends on the temperature and the permeability of the reservoir. In a wet geothermal field, flashing occurs at the well itself or possibly at the walls of the well where water enters it. In a dry field it occurs within the reservoir. It takes place, moreover explosively, so that rock fragments are ejected.

If the water recharge rate is insufficient to balance the discharge of steam, an evaporation space will form around the base of a well. This space will grow in size and may eventually join the evaporation spaces of other producing wells, so that a comprehensive steam zone may form above the water reservoir. Evidence from certain geothermal fields shows that the steam/water interface in such cases tends to fall if production is high. This process is likely to be asymptotic, owing to the higher rate of recharge as the level falls [12].

In J. R. McNitt's opinion [4], although thermal manifestations and evidence of recent volcanism may be found throughout the faulted belt, the most likely place to find the largest and hottest thermal systems is along its frontal border. This is because the whole tectonic zone migrates with time from the hinterland towards the foreland region so that the frontal border of the normal fault zone is also its youngest part. A good example of this relationship is in North Island, New Zealand, where the largest thermal systems are located in an arcuate zone adjacent to the Kaingaroa Plateau, which borders the fault belt on the east. Some orogenic zones have a distinct bilateral asymmetry, with the normal fault belt forming the central axial zone and the folded and thrusted zones flanking the axial zone on either side. The horizontal component of tectonic movement, as reflected by plateau tilts, monoclinal dips, inclined fold axes and thrust faults, is directed away from the central normal faulted zone on both its flanks. The axial region, or hinterland, of these bilateral zones is exceptionally wide and gives rise to vast regions suitable for geothermal prospecting. An excellent example of such a zone is the Alpine orogenic belt extending from Slovakia, through Hungary, western Romania, eastern Yugoslavia and southern Bulgaria to Macedonia. From the Greek coast it crosses the Aegean Sea to the western

coast of Turkey, and from there it crosses central Anatolia to western Iran. This whole region appears to be characterized by normal faulting, high heat flow, thermal springs and young volcanism. Its extension to the east of Iran, although not well documented, is highly probable.

In choosing the region of specific prospect areas, the best guides are thermal manifestations. Hot springs are such extraordinary and easily recognizable phenomena that, except for the most remote and uninhabited areas, their existence is generally known to local residents. After the thermal manifestations are located, the following information should be collected:

- type, i.e., fumarole, steaming ground, spring, well, seepage, CO_2 vent, etc.,
- temperature,
- flow rate,
- local geological control, and
- chemistry.

The objective of collecting this data is to have a basis for comparing the relative merits of the various thermal areas under consideration. Surface manifestation may reflect conditions at depth directly, or very indirectly, depending on the extent to which the thermal system is masked by overlying nonthermal ground water horizons. For examples, it is tempting to use surface heat discharge as a first approximation of a system's size, and therefore its capacity to produce usable energy. This assumption, however, can be misleading. Such major thermal systems as the Geysers and Salton Sea fields in the U.S., the Larderello fields in Italy, and the Matsukawa field in Japan have very meager surface heat discharge compared with the amount of energy released by drilling. The capacity and spread of dry steam fields (vapor-dominated systems) are particularly difficult to estimate from surface manifestations because the very existence of such systems requires a lithological or hydrologic "capping" which allows pressure, and therefore temperature, to build up in the trapped vapor. This same capping, however, prevents the escape of excessive discharges that could indicate the size of the system [4].

Surface manifestation. An abnormally high heat flow often, though not always, gives rise to surface manifestations, such as:

- warm or hot springs, steaming ground, steam vents and geysers;
- hydrothermal rock alterations;
- silica and travertine sinter:
- abnormally warm ground water temperature;
- fumaroles and solfatares;
- mercury ores of recent origin;
- hot soils, sometimes revealed by anomalous snow melting;

It should be remembered that thermal anomalies can exist without associated surface manifestations (e.g. Monte Amiata) and also that such manifestations have sometimes failed to lead to a commercially exploitable field.

Hot springs can originate from:

- deep circulation and resurgence through a permeable fault in an area of normal, or near normal, heat flow;
- local exothermic geochemical phenomena, such as anhydrite to gypsum or sulphide oxidation;
- heating by lavas not yet cooled, or by the molten magma of valcano;
- heating by magmatic intrusion.

Springs of the first type may be indicative of a hot water field of the type described above; those of the second and third types are more or less worthless economically; those of the fourth type are indicative of good economic prospects.

Certain types of hot springs or steam vents have been described as "leakage manifestation". It is suggested that water boiling at depth in a deep reservoir could pass up to the surface through a fault (often an active one) much as it would pass up a well. This water would flash into steam and may condense by cooling near the surface. The condensed water would differ chemically from normal surface water and its unusual character could also be detected after admixture with surface water. Sometimes there can be a leakage of gas, from the upper zone of a reservoir, through a fault to the surface, where it heats and mixes with ground water, thus giving rise to a hot spring rich in gases. An analysis of these gases can enable the temperature of origin to be deduced.

Hot springs having a high discharge rate of water may imply an aquifer at the same, or slightly higher, temperature.

Many hot springs deposit impressive siliceous and travertine sinter, which may be large and thick. Siliceous sinter deposits are indicative of a high-subsurface temperature at the time of deposition: travertine deposits may imply low temperatures [12].

Reservoir temperature and gradients. Individual thermal areas are characterized by the reservoir temperature. This figure represents the upper limit to the temperature of the fluid that can be produced by drilling. The production temperature will always be below the reservoir temperature. The highest reservoir temperatures have been recorded in large thermal areas to Iceland, Italy and New Zealand. It is noteworthy that three major thermal areas now being exploited, namely the Hengill in Iceland, Larderello in Italy and Wairakei in New Zealand, all appear to have a reservoir temperature in the range between 230°C and 250°C. The geological conditions in the areas are nevertheless quite different. These areas, having the highest temperatures on record, are potent sources of natural steam at pressures up to around 20 atmospheres and temperature up to about 200°C [8].

The energy in a geothermal reservoir consists of heat stored largely in rocks and, to a lesser extent, of liquid water or steam stored in pores and fractures. The water and steam provide the means by which the heat from deep sources is transferred by convection to depths shallow enough to be tapped by drilling. They also serve as agents by which the geothermal heat escapes through conduction at the surface in the form of hot springs or fumaroles. For a geothermal reservoir to be of appreciable economic potential for exploitation, it must have:

- relatively high temperature (66 to 210^{o}C);
- depth shallow enough to permit drilling (about 4000 meters or less);
- sufficient rock permeability to allow the heat transfer agents (water and/or steam) to flow continuously at a high rate; and
- sufficient water for recharge to maintain uninterrupted production [64].

All known high-temperature geothermal resources are located in areas of recent volcanic activity and are no doubt closely related to volcanism. There is little doubt that magma transported by the volcanic processes is in some way or other the ultimate source of the heat causing the thermal activity. The geothermal areas are probably convective systems drawing on the heat content of recent intrusives. Volcanism is a relatively common phenomenon, distributed all along the Circum-Pacific Belt, on the Mid-Atlantic Ridge, and in other locations in Asia, Africa and Europe. Thermal activity, on the other hand, is not nearly as common as volcanism. The volume of rock affected by thermal metamorphism is enormous and the hydrothermal phenomena are of much greater importance than actually indicated by the surface display. It is by no means inconceivable that one of the reasons for relatively few areas with surface display is found in the phenomenon of selective transport of materials in thermal areas. The possibly surface outlets are closed relatively rapidly by the precipitation of silica and calcium carbonate at and near the surface. The deeper processes may remain relatively unaffected.

Such areas, with closed surface outlets but some convection at depth, would be characterized by a relatively large conduction flow of heat in the surface layers. It should be possible to locate them by means of a study of the temperature gradient in shallow boreholes. Unfortunately, very little is known about the variations of the temperature gradient. There are practically no data at hand from most volcanic areas, probably because these areas are regarded as abnormal. But the degree of abnormality is the point of present interest.

Summing up, it can be stated that there are reasons for expecting hidden geothermal resources in volcanic areas and there is as yet no observational evidence contrary to the hypothesis.

There are rather small possibilities for low temperature geothermal resources in nonvolcanic areas. The average temperature gradient in such areas generally varies from 10 to $50^{\circ}C/km$. However, the upper limit is not altogether uninteresting. An increase of $50^{\circ}C/km$ implies 50° to $60^{\circ}C$ at a depth of 1000 meters, and 100 to $110^{\circ}C$ at a depth of 2000 meters. It should be possible in some nonvolcanic areas to drill without excessive cost into horizons having a temperature of around $100^{\circ}C$. Such horizons, if porous and permeable, are possibly reservoirs of water at a temperature around $100^{\circ}C$, which is sufficient for space heating [8]. Holes for thermal gradient measurement must be drilled deep enough to penetrate any surface formations liable to be disturbed by ground water movement, and they should extend far enough into the undisturbed zone below to give reliable gradients. Although it may sometimes be possible to estimate the thickness of the disturbed layer from geological or other evidence, it is very desirable to check whether a hole is deep enough by measuring temperatures at multiple points spaced about 2 1/2 m apart over the bottom 20 m of the hole. If the measured temperatures fall on a straight line when plotted against depth, the deduced gradient is probably reliable; otherwise, the hole must be deepened or the area avoided. In general, very little will be learned by drilling gradient holes too close to the areas of surface activity; the gradient will be subject to disturbance by upward

movement of hot water or steam, and the holes will be liable to erupt.

If gradient holes are drilled on a regular grid pattern with a spacing of 1 km, a thermal anomaly of reasonable size (covering, say, 10 km^2), could be mapped, inclusive of margin areas, with an array of 20 to 30 holes. A hole density of this order should suffice for all but the most detailed mapping, since experience has shown that lateral temperature variations below the surface convective zone are generally not very rapid. Additional holes could, however, be necessary in some fields if marked discontinuities in the temperature pattern indicate corresponding structural features, such as faults, contacts, etc., which might in some cases also be checked against geological data. As a general rule these gradient holes would be too shallow (30 to 40 m) to provide much new information about structure, but coring for geophysical or geological information could be profitable, at least on a trial basis, in a few holes.

For actual temperature measurements various instruments may be used. For temperatures much over 100°C a geothermograph or Amerada gauge is suitable. For lower temperatures it may be convenient to use thermo-couples, thermistors, platinum resistance thermometers, or even mercury maximum thermometers with proper precautions. Electrical instruments can be wired up differentially so as to measure the gradient directly, though this is seldom done in practice. Care must be taken, with electrical instruments, to ensure that the cable insulation is suited to the temperatures to which it is exposed. Nylon or PVC is suitable for moderate temperatures, while mineral insulation or such materials as "Teflon" may be required for higher temperatures [19].

a. Conductive thermal gradients

Temperatures below the earth's surface are principally controlled by the conductive flow of heat through solid rock, by convective flow in circulating fluids, or by mass transfer in magma. Transfer in magma is considered only through its effects on conduction and hydrothermal convection. Conduction is the dominant mode of heat flow in most of the outer

crust of the earth. Where conduction is dominant, temperature increases continuously with depth, but not at constant gradient. The important interrelations are those between thermal gradient, heat flow, and thermal conductivity of rocks. The measured thermal gradient is directly proportional to heat flow but inversely proportional to conductivity. Heat flow is the most fundamental parameter but usually must be calculated from gradient and conductivity because, at low levels, heat flow cannot be accurately measured by any direct method.

In an area dominated by conduction and free from significant convective disturbances, heat flow is relatively constant in time and space, but conductivity of rocks varies greatly with depth as function of mineralogy, porosity, and fluid content of pores. Therefore, temperature gradients may change greatly with depth, as in curve B of Fig. 3, which shows the effects of variable thermal conductivity on thermal gradients, as compared with rocks of constant conductivity (curve A). A near-surface gradient cannot be

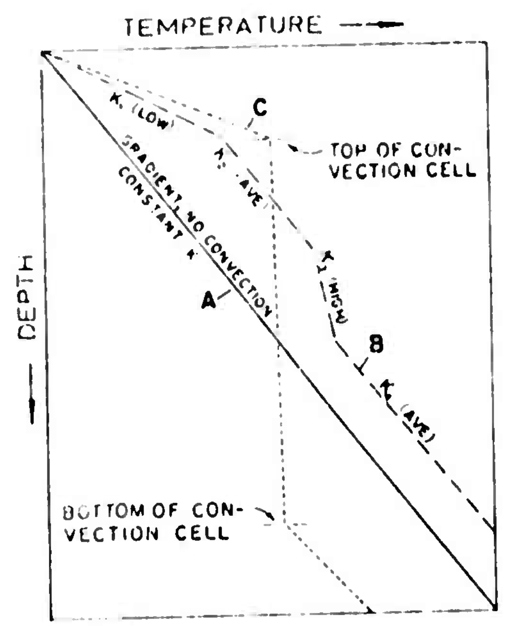

Fig. 3. Temperature/depth relations, where heat flow is controlled by thermal conduction in rocks of constant conductivity (A), or rocks of variable conductivity (B), or by major convective disturbance (C)[17].

reliably projected downward below explored depths because of likely changes in porosity and thermal conductivity with rock type and, especially, until possible convective influences can be evaluated.

For areas of near-normal conductivity thermal gradient, the worldwide average heat flow is about 1.5 μcal/cm^{2}sec, or 1.5 hfu (geothermal heat-flow unit). This is about 1/2000 of average solar energy at the earth's surface; a very small quantity but an important one. For present purposes, the "normal" heat flow ranges from 0.8 to 2.0 hfu. The thermal conductivity of most rocks ranges from 4 to 10 mcal/cm sec $^{\circ}$C. Within these limits, temperature can increase from 8° to 50°C/km, averaging about 25°C/km or slightly higher. At 3 km depth, with such gradients, temperatures range from 24° to 150°C above surface temperatures and average about 75°C. Most "normal" areas are not attractive for commercial geothermal exploration, either now or in the immediate future, and their stored heat should not be considered as usable resources, much less as reserves recoverable under present conditions. Some areas may have a combination of heat flow in the higher part of the "normal" range and conductivity in the lower part of "normal". Such an area is the Gulf Coast of the U.S., where gradients range up to 45°C/km or slightly higher. However, such areas may prove to be exceptions warranting further study and evaluation, especially where existing oil and gas wells are already available for research use.

Abnormally high conductive thermal gradients result from unusually high heat flow, unusually low thermal conductivity, or favorable combinations of the two factors. In some large favorable areas, such as the Hungarian Basin, conductive gradients range from 40° to 75°C/km, and perhaps locally even higher.

b. Hydrothermal-convective systems

In hydrothermal-convective systems, most heat is transferred in circulating fluids rather than by conduction. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field;

heat, which is supplied at the base of the circulation systems, is the energy that drives the system. Heated fluid of low density tends to rise and be replaced by cooler fluid of higher density, which is supplied from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease. Gradients are commonly very high near the surface, and locally exceed $3^{\circ}C$/meter of depth. Such a gradient, projected, exceeds $3000^{\circ}C$ at 1 km and is impossibly high, greatly exceeding the melting temperatures of all normal rocks (700° to $1200^{\circ}C$). Temperature gradients in convection systems tested by drilling, have been shown to decrease greatly with depth until the characteristic base temperature of the circulation system is attained. Locally, temperature reversals may occur [17].

For heat flow determinations, temperatures are measured with a thermistor thermometer, a transducer, and surface equipment for commercial well-logging units. Heat production measurements and the content of uranium, thorium and potassium are determined by gamma-ray spectrometric techniques [24].

Two major types of hydrothermal convective systems are recognized, which differ in the physical state of the dominant pressure-controlled phase:

(1). Hot water systems, containing a water reservoir at temperatures ranging between 60 and $100^{\circ}C$, can be used for space heating, agriculture and various industrial purposes. The thermal gradient in fields of this type may range from normal (about $33^{\circ}C$/km) at which hot water of useful temperature would occur at depths from about 1800 to 3000 m, to values of about twice the normal or more. Examples of the latter are the Hungarian Basin (40 to $75^{\circ}C$/km) and the Arzag Basin in Southern France ($60^{\circ}C$/km gradient), and many regions of the USSR. At these higher gradients the hot water is encountered at shallower depths [12].

Hot water systems are characterized by liquid water at the continuous, pressure-controlled fluid phase. Some vapor may be present, generally as discrete bubbles in the shallow, low-pressure zones. Continuity of liquid can be inferred with confidence from the distribution of pressure and from the abundance of constitutents that are soluble in liquid water but have low vapor pressure and lack significant solubility in low-pressure steam. These include most of the constituents of ordinary water analyses, such as SiO_2, Na, K, Ca, Mg, Cl, SO_4, HCO_3, and CO_3 (though B, CO_2, H_2S, and NH_3 are both volatile and soluble in water, and thus are not diagnostic).

Water in a major water-convection system serves as the medium by which heat is transferred from deep sources to a geothermal reservoir at shallower depths where it is tapped by drill holes. Cool water percolates underground and then circulates downward. At depths of 2 to 6 km, the water is heated by conduction from hot rock that, in turn, is probably heated by molten rock.

However, hot-water systems actually include many subtypes that are not yet universally accepted or precisely defined. Different classifications can be based on total salinity, dominant chemical characteristics, temperature range, structural and stratigraphic environments, presence or absence of permeable reservoirs, and insulating cap rocks. The following are some subtypes of particular interest to geothermal exploration:

<u>Low to moderate temperatures systems,</u> generally ranging from about 50 to 125°C in most cases but may reach as high as 150°C in Iceland. They are characterized by chemical similarity to surface and shallow ground waters of the region. Some systems in the higher part of this temperature range may be characterized by impressive boiling springs of high discharge.

Deep sedimentary basin systems, which commonly bear saline waters of moderate temperature similar to oil field waters. These waters are, at least in part, nonmeteoric in origin.

Hot-water systems which are known to contain brines of very high salinity. The Salton Sea geothermal system and the Red Sea brine pools contain brines of about 26% salinity, but different temperature relationships and bulk chemistry.

Systems with natural cap rock that tend to inhibit discharge and also to insulate their reservoirs, thus conserving the heat.

High-temperature hot-water convection systems that tend to create their own insulating cap rock by self-sealing; hydrothermal minerals are deposited in pore spaces, especially in near-surface parts where temperatures decrease abruptly upward because of the influence of the boiling point curve [17].

The geology of hot water fields is much the same as for cold ground water systems. Systems suitable for commercial exploitation may be of the buried type (artesian) or the open type (without a cap rock).

Hot water systems of this low-temperature type are quite common and may be worth investigating for commercial exploitation in areas where: a large water reservoir is believed to exist at temperatures of at least 60°C at less than 2000 m depth; the heat flow is at least 2.2μcal/cm^{2}s (about 50% above world average); and the yield per well is large.

Wet steam systems, which contain a pressured water reservoir at temperatures exceeding 100°C. This is the commonest type of economically exploitable geothermal field. Notable examples under exploitation are Wairakei (New Zealand), Cerro Prieto (Mexico), Reykjavik area (Iceland), the Salton Sea (USA), and Otake (Japan). The hottest known field in Cerro Prieto (380°C).

When hot water is brought up to the surface, and its pressure is sufficiently reduced, some of the water will be flashed into steam, so that the resulting fluid is a mixture of water and steam under saturated conditions, with water usually predominating. The proportions of water and steam vary from field to field, and from well to well in a single field, according to the enthalpy of the fluid at depth, and the pressure at the wellhead. A productive well in this type of field will continue to flow after the flowing process has been initiated. Such fields can be suitable for power generation, as well as for other purposes [12].

(2) Vapor-dominated systems, also know as dry steam systems, are those that yield dry or superheated steam with no associated liquid. For this reason they are commonly known as dry systems, but some scientists conclude that liquid water and vapor normally coexist in the reservoirs, with vapor as the continuous, pressure controlling phase. Thus vapor-dominated system seems to be a more appropriate term [17].

Geologically, wet steam and dry steam (vapor dominated) systems are generally similar, emphasized by the fact that in some cases wells have produced wet steam for an initial period and dry steam later.

The degree of superheat may vary from 0 to 50°C. Examples of this type of field under exploitation are Larderello and Monte Amiata (Italy), the Geysers (California, U.S.), and Matsukawa (Japan). This type of field is suitable for power generation and other purposes [12].

Two subtypes of the vapor-dominated system which appear to be distinguishable are:

Larderello subtype. The physical, chemical and geologic characteristics of the Geysers, Larderello, and Matsukawa vapor-dominated systems are consistent and may be summerized as follows:

• Reservoirs occuring at or below about 300 m in a depth tend to have initial temperatures near 240°C and pressures near 35 kg/cm^2.

• The relatively uniform initial temperatures and pressures are strongly influenced by the maximum enthalpy of saturated steam (669.7 cal/g at 236°C and 31.8 kg/cm^2). As the gas content of the vapor increases a few percent, these physical characteristics change greatly. For example, at a constant temperature of 236°C for coexisting liquid and vapor, 1% of other gases in the vapor increases the total pressure to only 32.1 kg/cm^2. But the corresponding pressure of 5% of the other gases is 33.5 kg/cm^2, and that for 10% is 35.3 kg/cm^2.

• Pressure in these vapor-dominated reservoirs are well below hydrostatic and, with few exceptions, the difference increases with depth. Obviously, such a system could not form or persist if the water-saturated rocks that surround the reservoir supplied a high rate of recharge. The water thus supplied would flow into the reservoir under hydrostatic drive at a rate exceeding discharge, and the underpressured reservoir would collapse.

• Fumaroles, mud pots, mud volcanos, turbid pools, and acid-leached ground characterize the discharge areas where surface activity is most intense. Springs in such areas are generally acid because of the H_2SO_4 produced by oxidation of H_2S in the escapting gas; pH's are as low as 2 to 3 except where NH_3 is abundant enough to neutralize the acid. Sulfate contents tend to be high, but Cl contents are uniformly low (< 15 ppm). Likewise, the springs, streams, and ground water of the immediately surrounding area are low in chloride. Areas lacking intense surface activity are characterized by slightly acidic to slightly alkaline bicarbonate-sulfate spring waters that may be high in total CO_2, B, or NH_4, but low in Cl. Some spring waters of such areas are also anomalously high in SiO_2.

- Production wells normally produce dry to superheated steam (from a few degrees to more than $50^{\circ}C$ of superheat). However, liquid water evidently occurs in some noncommercial wells on the borders of reservoirs and in the fluid initially produced from some wells that change from wet steam (i.e. steam containing a little water) to dry steam.

- Most of the heat content of the reservoir is stored in solid phases which generally carry 80 to 90 percent of the total heat.

- Superheated steam forms from saturated steam by flow and decompression through hot rocks already dried by transfer of heat from solid phases to evaporating pore liquid. Critical aspects of these relationships are the stored heat of solid phases and the decrease in boiling temperature with a decrease in pressure.

The previous discussion is concerned chiefly with systems such as Larderello, The Geysers, and Matsukawa that are characterized by initial reservoir temperatures near $240^{\circ}C$, shut-in pressures near 35 kg/cm^2, and contents of gases (other than steam) of about 5 percent or less. Discharge areas seem essential for such systems, permitting the net loss of much initial pore water to establish domination by the vapor phase, and flushing out gases other than steam. A large system is likely to have at least one prominent vent area that cannot be accommodated by discharge into ground water. Under some circumstances, less vigorous discharge of steam and gases can be accommodated. The flow of fluid in systems of this subtype is limited by the low permeability of the recharge channels. These channels constitute the limiting impedance of fluid flow throughout the system.

Monte Amiata subtype. A second variant of vapor-dominated systems, referred to as the Monte Amiata (Italy) subtype, is still not well understood, but is evidently similar in many respects to hot natural-gas fields. Temperatures tend to be much lower (about $150^{\circ}C$) and initial gas contents tend to be much higher (>90 percent), with initial pressures of about 20 to 40 kg/cm^2. Thus, steam is a relatively minor initial constituent,

presumably because of condensation of water vapor near the relatively cool borders of the reservoirs. During production and decompression, the initial vapor of high gas content is flushed out of the reservoir and is replaced by the relatively low-pressure steam of low-gas content that results from water boiling at only a modest temperature. Another characteristic of the fluids produced from the Bagnore field of the Monte Amiata district is a trend from dry vapor to vapor plus liquid H_2O. The most restrictive impedance to fluid flow for the Monte Amiata subtype evidently occurs in the discharge part of the system, where low-permeability cap-rocks limit the discharge of gases to rates that are equal to or less than rates of generation or supply of gases. In contrast to the Larderello subtype the discharge of gases and steam is not required to form or maintain vapor-dominated reservoirs of the Monte Amiata subtype, although some leakage of gases is no doubt characteristic of most reservoirs.

c. Problems of utilization

Consequent problems of large-scale utilization of various geothermal field types and subtypes are manifold. Some basic major problems are:

- Because of its special geological and physical requirement, the commercially attractive Larderello subtype of the vapor-dominated systems is rare, accounting perhaps for only 5 percent of all geothermal systems with temperatures above 200°C. The advantages of the subtype for utilization are presently demonstrated by a dominance of geothermal power-generating capacity (an estimated 73 percent of the world total, operating or under construction through 1973).

- A discharge area is probably essential for the Larderello subtype, with characteristic, recognizable manifestations of activity, chemistry, and ground bleaching. If so, then completely concealed deep systems are not available for future discovery.

- The Monte Amiata subtype of vapor-dominated systems, characterized by a relatively high content of noncondensable gases and moderately low temperatures may be more common than the Larderello subtype but more difficult to discover because of the absence of conspicuous surface characteristics. Because of its physical and production characteristics this subtype is not attractive for exploitation (about 2.3 percent of the world total through 1973).

- The high-temperature, hot-water fields (about 25 percent of the world total through 1973) are attractive for near future increases in power production, but present utilization technology is not efficient; converting only about 1 percent of stored reservoir energy into equivalent electric energy.

- The water of many hot-water systems, when flash-erupted and cooled, deposits SiO_2 or $CaCO_3$ in wells and surface pipes. If similar flashing and mineral deposition occur in the reservoir immediately adjacent to wells, permeability and production rates decrease drastically.

- Some hot waters are corrosive because of high salinity, high CO_2 or O_2 content, or high acidity from H_2SO_4, or, rarely, HCl.

- Some hot water systems do not have adequate volume, temperature, or permeability to maintain commercial production. From general experience at Broadlands and Waiotapu, New Zealand, and Beowawe and Steamboat Springs, Nevada, inadequate permeability and reservoir characteristics may be as common as inadequate temperature.

- Most hot water effluents involve some environmental hazard, since they are generally higher in dissolved salts, B, NH_3, As, and heavy metals than are most surface and ground waters. Such effluents will require disposal by some satisfactory means, with reinjection generally favored.

• Some hot water effluents may not be compatible with reservoir or other formation fluids, even though the fluids are initially identical. Compatibility and reliability of reinjection must be tested, and better principles for early recognition of the attendant problems must be developed. Reinjection was tested for one year in the Salton Sea system and for short intervals in the Long Valley system of California and the Ahuachapan field of El Salvador, but the only long-sustained test (about 3 years through 1972) was at the Geysers in California. In the latter field, cool condensate is successfuly reinjected into an underpressured vapor-dominated reservoir; presumably much of the liquid is vaporized by transfer of heat from the still-hot rocks. These results are interpreted as proof that reinjection elsewhere will be equally successful. However, because individual hot water systems vary greatly in fluid chemistry and precipitation potential, such a conclusion is hazardous without adequate testing. Production engineers estimate that if reinjection is successful for one year, the process can be continued for several more years.

• Most chemical problems are not serious for the low-temperature, hot-water systems, but self-eruption is unreliable or lacking for water that is too low in temperature or that must be "steam-lifted" from depths far below the ground surface. The percentage of water that flashes to steam in a producing geothermal well depends mainly on the initial temperature and the pressure of steam separation from residual water, with liquid constituting 70 to 90 percent of most commercial production. The steam-lifting of moderate temperature waters (150° to 200° C) becomes increasingly less effective as reservoir pressures and temperatures decline with production. As water levels (fluid potentials) decline below the ground surface, the energy required to lift liquid water increases. Thus, such water probably must be pumped to be produced at all.

• Desalination of low-temperature waters involves more chemical and effluent-disposal problems, since the dissolved solids are concentrated into a small proportion of residual water. Soluble constituents,

such as NaCl , normally will not precipitate, and constitutents of low to very low solubility, such as SiO_2, $CaCO_3$, and $CaSO_4$, are potentially troublesome.

- Thermal noise, and air pollution (principally H_2S) may constitute environmental hazards requiring some control, depending on their severity.

- Seismic hazards from reinjection must also be eval ted, especially for hot-water systems. However, reinjection into underpressured, vapor-dominated systems should involve little or no seismic hazard.

- Subsidence will occur over hot-water reservoirs consisting in part of clay, silt, or shale where produced water is not locally replaced by reinjection. Sand and sandstone are less subject to compaction, unless pore fluids are overpressured. However, subsidence over vapor-dominated reservoirs (initially already underpressured relative to hydrostatic) is likely to be slight [17].

Concerning of oil and gas reservoirs, the principles of energy conservation and mass have been developed into an extremely powerful tool in reservoir engineering, providing in many cases a reliable estimate of the amount of energy initially in place. The application of this method is dependent on a period of exploitation which has had measureable effects on underground conditions in the field. Unfortunately, the development of these principles as they apply to geothermal reservoirs has not yet resulted in a similar available method of analyses. One probable reason for this is that presently there are very few geothermal fields with any substantial production history. The number of geothermal fields under exploitation is increasing, presently there are few with a production history indicating the effects of exploitation. The examples discussed below are the Wairakei field in New Zealand, the Larderello field in Italy, and the Laugarnes field in Iceland. The first is basically a high temperature hot water system, the second a dry steam system, and third a low temperature (less than 150°C) hot water

system. In this respect, they can be regarded as typical of main types of geothermal systems.

<u>Wairakei field.</u> The production history of this field extends over nearly 20 years, and in that time substantial changes have taken place in the underground conditions. The production aquifer is a breccia about 1,500 ft thick, overlain by a mudstone/siltstone formation which acts as a cap rock. Useful production is obtained from the breccia, but the best production is from the contact between the breccia and the underlying ignimbrite at a depth of about 2000 ft. Initially, the aquifer was filled with water, temperature and pressure conditions following the boiling point for depth relationship. The maximum temperature measured in the field was 260°C.

Exploitation has resulted in an almost uniform pressure decline of over 300 psi and affecting an area considerably greater than the main production area. This is indicative of the very high horizontal permeabilities in the field. Figure 4 shows the relationship between rate of pressure decline and rate of discharge.

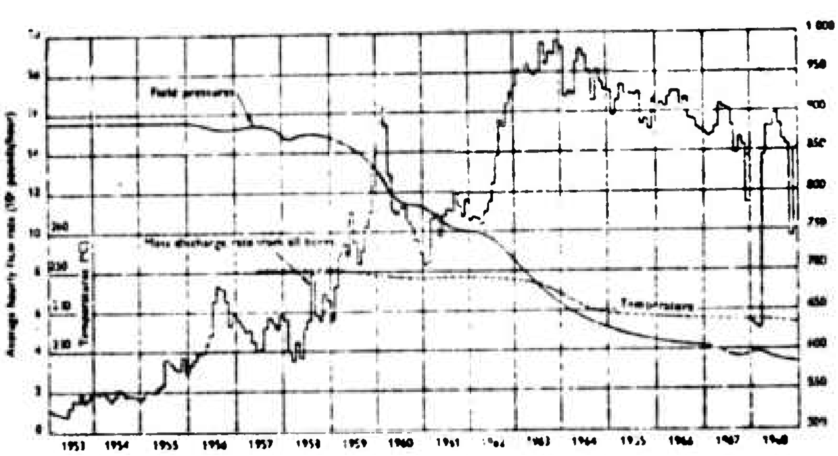

Fig. 4. Wairakei field discharge rate and pressure [13].

As can be seen, this is not a linear relationship because while there is an immediate fall in pressure following an increase in discharge,

a prolonged period of substantially constant discharge shows pressure tending toward a stable value. The relationship between pressure and discharge suggests that conditions were influenced by an inflow, which is supported by the rise in pressure at the beginning of 1968 in a period when the field discharge was reduced to about 1/3 the normal rate.

Temperature trends in the upper levels show a similar pattern as illustrated in Fig. 4. The temperature trend shown is for the average of the maximum temperatures in the wells in the western or main production area, and reflect the temperatures in the production area. It is important to note, that temperatures at greater depths have shown no changes. Except for the first quarter of 1968, the number of wells on production has been substantially constant since 1963, but there has been a gradual decline in output. The average life of a Wairakei well is difficult to determine precisely. Of the total 68 producing wells which have been used, seven have been abandoned (two due to broken casing and five because their discharge pressure fell below the steam main pressure). The average age of these seven wells when abandoned was 9 1/2 years. The average of the remaining 61 is 13 years, and of these 4 have been producing for over 19 years.

The main decision on field management resulting from a study of the field behavior is that it would be unwise to attempt any further increase in the discharge. This has meant dropping the proposal to bring the installed capacity to 250 MW as initially planned, and also dropping a proposal to develop the outer area separately. The reason is that any substantial increase in discharge will result in a future decline in pressure, temperature, and well output.

<u>Larderello field.</u> This field has been under exploitation for many years, initially for the recovery of chemicals, and since the mid 1920's, for the generation of electricity. Here, as at Wairakei, substantial

changes have taken place. It has not been the practice of Larderello to measure formation temperatures and pressure, but the nature of the field is such that changes in formation conditions can be inferred from wellhead measurements.

Figure 5 (Bugassi, 1964) shows the changes which occur in the output, and the wellhead pressures and temperatures in a typical well in the heavily exploited Larderello area. In lightly exploited areas, the output of a well will remain constant for the years. The life of a steam well at Larerello is estimated to be 20 years (Chierici, 1964), but some are still discharging after 30 years, although at a greatly reduced output.

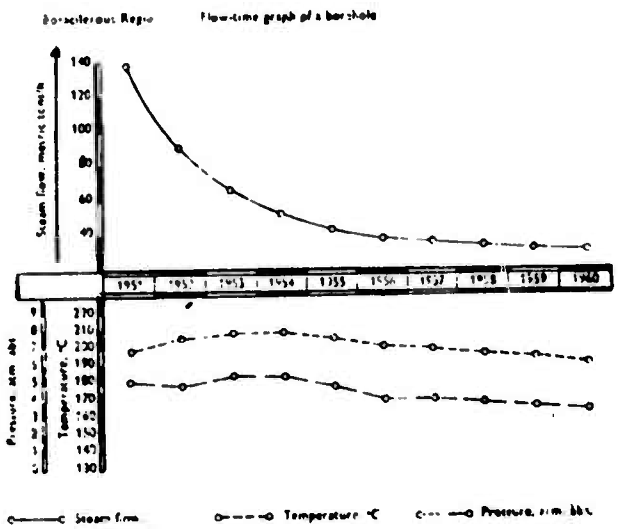

Fig. 5. Larderello well output characteristics [13].

The most significant change which has taken place in the Larderello field is that where the discharge from the initial deep bores was saturated steam, it is now dry with an appreciable amount of superheat. This is attributed by Chierici (1964), and Ferrara et al (1970) and others to a gradually receding boiling water surface at depths in excess of 2 km. The steam produced is superheated by passing through layers of rock which, due to their poor conductivity, have retained heat.

A feature of the management of the Larderello field has been the need for a continued drilling program to maintain the total output, the new wells being drilled relatively deeper. Presently a number of production wells are operating close to their shut-in pressure, and exploration is continuing at still greater depths with the goal of locating higher pressures.

Laugarnes field, Iceland. This field has been under exploitation since 1928 for district heating of the city of Reykjavik. Initially, production was from shallow artesian wells, but since 1962 it has been solely from pumping deep wells. Production is from three aquifers. Temperatures in the upper aquifer, which is 200 m below ground level, are 110-120°C. In the middle aquifer, the temperature is 135°C, and in the lower, about 2200 m below ground level, it is 146°C. From 1957 to 1962, the discharge rates were relatively uniform as the flow was mainly artesian. Since 1962, following the introduction of deep well pumping, the flow has varied seasonally, the winter flow being about three times the summer flow. The winter peak discharge is accompanied by a draw-down in aquifer pressure which is almost entirely recovered during the summer. From January 1957 to August 1969, the net decline in pressure was equivalent to 66.8 m waterhead. No effect on temperatures at depth has been reported.

In summary, substantial exploitation of any underground fluid will result in a decline in pressure of the system, and geothermal systems are no exception to this rule. In the case of fields discharging under thermo-artesian conditions, outputs also decline. The extent of the decline in output and pressure is governed by the replenishment rate of the discharged fluids, which in turn is a function of the permeability of the system as a whole. Presently, the magnitude of these effects cannot be predicted from early investigations, and can only be assessed after a period of exploitation. This is the fundamental reason why a geothermal field must be developed in stages.

In thermo-artesian systems, the discharge capacity of individual wells decreases with increasing exploitation. This indicates that when selecting an operating pressure, the lowest pressure consistent with

the other factors influencing the choice should be adopted, as this will give the longest operational life for the individual wells.

In a high temperature hot water system such as Wairakei, in which saturation conditions apply in the upper levels, the fall in pressure must inevitably be accompanied by a fall in temperatures at these levels. The heat stored in the formation rock will tend to sustain temperatures causing a lag between the temperatures and pressure declines. Similar effects are shown by a steam system, but in this case the effect on temperature will be less pronounced. There can, however, be a substantial increase in enthalpy.

With non-thermo artesian systems developed by deep well pumping, the effects of exploitation on output are obscured by the pumping, but there will nevertheless be a decline in pressures. In this type of system, where saturation pressures for the measured temperatures are considerably lower than the hydrostatic pressure, it is unlikely that steam will form in the formations. Consequently, the principles of flow in porous media can be successfully applied, as has been done for the Laugarnes field.

The effects of exploitation on natural activity differ according to the nature of the field, and the time the field has been exploited. At Larderello, which has been exploited to varying degrees for over 100 years, the flow of heat from many of the areas of intense natural activity has almost disappeared. At Wairakei on the other hand, heat flow measurements in 1958 showed that the natural heat flow had not changed since 1952 although the field output was over 1 1/2 times the natural discharge. Subsequently, the field output has reached 6 times the natural discharge and, although no precise measurements are available, there is no noticeable decrease in the natural heat discharge. There has, however, been a noticeable increase in the enthalpy of the discharge. This is evident in the decline in or cessation of discharge from hot pools and springs, and an increase in area and intensity of heat escape from steaming ground, occasionally accompanied by small eruptions [13].

One or more of several potentially important breakthroughs in utilization technology may greatly expand the development of geothermal systems, in the immediate future. The most significant of the possible breakthroughs are:

- Heat-exchange technology that would permit utilization of the heat from fluid down to 100°C or less, since total heat contained in easily recoverable natural fields at temperatures of 100-180°C is far greater, perhaps by a multiple of 100, than total easily available heat above 180°C.

- Multipurpose developments, including desalination and/or chemical recovery, that would yield significant sharing of total costs.

- Low-cost mechanical, chemical, or nuclear fracturing of hot, dry rocks to increase permeability, thus permitting introduction of fluids and recovery of stored energy.

- New methods for drilling low-cost holes to great depth.

- New technology or other developments that favor wide applications to space heating, horticulture, and product processing.

- Solution or control of all geothermal resource problems at no greater cost than corresponding environmental and other problems of competing sources of power.

Some of these breakthroughs could have profound effects on the recovery of geothermal energy from very large gradient-dominated volumes of rocks, such as the deep sedimentary basins and hot, dry crystalline rocks, which are unlikely to be utilized within present prices and technology.

Strikingly disparate estimate have been made in recent years for the power potential, desalination potential, relative cost, and environmental-pollution aspects of geothermal energy. Depending on the source, the expressed

view ranges from conservative (locally important, but with a relatively small potential for supplying national needs) to highly optimistic (very promising, with implied reliable potential for supplying a major part of all future needs for both power and desalinated water). The discrepancy is related largely to:

- a lack of agreement on the various categories of resources with respect to certainty of existence and feasibility and cost of recovery,

- differing assumptions on future technology and on whether hoped-for breakthroughs are likely to be realized with reliably predicted costs, and

- a lack of agreement on the characteristics and nature of different types and subtypes of geothermal deposits, with respect to individual problems of discovery and energy recovery.

In D. E. White's opinion [17], world geothermal power production is unlikely to exceed 30,000 MW with present prices and technology. However, the geothermal resource base (total stored heat, without regard to cost of recovery) can be estimated with some reliability and depending only on the assumed depth (3 km, 10 km, etc.) and thermal gradient, by the concept of volumetric specific heat can be utilized. He assumed an average gradient of $20^{\circ}C/km$ and calculated 3×10^{26} cal of stored heat (i.e. heat above surface temperatures) under the surface of the earth to a depth of 10 km, with 6×10^{24} cal of that worldwide total under the United States. The assumed average gradient may be too low, and $25^{\circ}C/km$ may be a more likely average, but even if an improbable $30^{\circ}C/km$ is assumed, the resource-base calculations are raised only to 4.5×10^{26} cal and 9×10^{24} cal, respectively [17].

In view of present experience it is possible to outline a number of characteristic features of geothermal reservoirs which are capable of sustaining power generation in the 100 MW range. The base temperature has

to be quite high, or preferably 200°-300°C. The reservoir volume has to be at least of the order of several hundred cubic kilometers. The permeability of the reservoir rock must be adequate and ground water must be available in sufficient quantities. The depth to the ground water table should not be too great and the water should not contain dissolved solids in great quantities. The puming of geothermal boreholes is often advisable in order to improve production [25].

Estimation of reservoir capacity should enable a first estimate of the power potential. Taking the area indicated by the deep resistivity and surface gradient measurements, and the reservoir temperature implied by the geochemical studies, it is possible to deduce from the curves the approximate field potential in MW/years. Thus, for example, a thermal anomaly with a horizontal area of 10 km^2 and an inferred reservoir temperature of 260°C would have an estimated potential of about 4,000 MW-years, or sufficient to maintain an output of 200 MW for 20 years. This estimate is believed to be conservative, as it assumes a hot water system with a boiling point/depth distribution and an energy yield of only 25% of the theoretical [19].

B. Exploration for Geothermal Resources

The objectives of geothermal resources exploration are to locate areas underlaid by hot rock, to estimate their volume, temperature and permeability, and to determine the chemical composition of any producible fluids. In general, geothermal resources may be divided into four types:

- convective hydrothermal systems,
- geopressured systems,
- hot, impermeable rock, and
- magma systems.

Each type has its own physical properties and poses its own problems. Some of the more important problems are concerned with determining the age, size, and magmatic type of igneous occurences related to convective hydrothermal systems; the nature and cause of structural features controlling the location of convective hydrothermal and hot, impermeable rock systems; and the relationship of convective hydrothermal systems to broad regions of elevated heat flow.

Thermal exploration techniques provide a direct method for assessing the size and potential of a geothermal system. More regional heat flow determinations are needed to refine the estimates of available resources. And research is needed to determine the relationships between temperature gradients, subsurface isotherm patterns, and the geometry of geothermal systems. Laboratory temperature experimentation on model geothermal systems should be useful. Hydrologic studies are required to understand more fully the effect of groundwater movement on local geothermal gradients [6].

In general, prospecting methods for geothermal resources fall into two classes:

Direct methods which probe the subsurface temperature fields by thermal, electronic, chemical, and microseismic techniques, and

Indirect methods which are mainly applied to structural problems and include seismic, gravimetric, and magnetic techniques [60].

Moreover, the microearthquake technique which is still in its developing phase can also possibly be classified as a direct method [25].

These methods are substantially similar to those applied in the fields of hydrology, hydrogeology, and prospecting for oil, natural gas, and minerals [60].

Several prospecting methods with novel approaches are still in testing and evaluation stages. However, the measurements of temperature gradients and heat flow rates are still the basic and most direct methods in geothermal prospecting. Geophysical surveying by electrical resistivity methods for shallow- and medium-depth sites also is a present practice. In general, the electrical resistivity methods have proven very reliable in geothermal prospecting, because of the direct relationship between the fluid and rock temperature on one hand, and electric conductivity on the other. They owe their effectiveness to the fact that the resistivity of water decreases noticeably as its temperature and content of ionized salts (e.g., sodium chloride) increases. Prospecting by the resistivity method can be hampered by several geological parameters such as: porosity, high fluid salinity, cementation, and clay content. However, through the effective application of common geological techniques, it is possible at times to isolate electrical resistivity changes due to temperature alone, and to calculate the geothermal gradients [64].

However, the instruments for measuring heat flow, thermal conductivity variations, thermal gradients, chemical composition of water, and other elements of geothermy, are the same as those used in standard geological exploration and hydrogeological engineering. The Soviets have

developed an instrument used for evaluating such physical parameters as thermal conductivity, permeability, and heat flux in rock under dry or wet conditions. The method involves heating and pressurizing the center of blocks of different types of rock with or without addition of liquid solutions. Quite large blocks are used, up to tens of cubic meters, with internal temperatures up to 1,000°C. Temperature and pressure gradients are measured in the walls by probes [65].

Geochemical data collected during exploration are useful in all phases of evaluation, development, and utilization. Several hydrochemical indicators have been used successfully in geothermal exploration, but others are difficult to interpret. Therefore, research is needed in the chemical, physical, and thermodynamic properties of aqueous solutions at temperatures between 100° and 400°C; the relationship between the chemical composition of geothermal fluids and the temperature of the host rock; and the isotopic variation in geothermal waters.

In addition, geothermal systems exhibit variations in electrical resistivity, calling for research toward: understanding the effect of porosity, water salinity, and temperature upon electrical resistivity in geothermal reservoirs; improving electric-field techniques and procedures for extracting true resistivity values from field data; and developing complementary exploration techniques that will improve the interpretation of resistivity data. Electrical exploration research should include further research on deresistivity, self-potential, electromagnetic, telluric and magnetotelluric techniques [6].

The development of a geothermal field is based on an estimate of its energy potential, together with estimates of the economics of development. However, it is not possible to estimate the potential of a geothermal field with the same precision as for oil or gas fields. The nature of geothermal energy is such that it is extremely difficult to determine various limits, the main problem being in determining depth. Nevertheless, estimates can be made which, by comparison with similar estimates for fields under exploitation, form a reasonable basis for evaluating the economics of development. An

assessment of the natural heat flow at the surface is usually one of the first steps undertaken in the investigation of a geothermal field. It is suggested that it may be possible to produce a geothermal field at more than five times the rate of natural discharge. Unless the deep inflow increases correspondingly, pressure and temperatures and production rates will eventually decline.

From a knowledge of the field area, the distribution of temperatures, and the formation characteristics, the heat storage in the formations between various levels can be estimated. By making assumptions leading to an estimate of the recoverable stored heat, the potential for power generation can be assessed. Estimates of this nature can be used as a basis for decision on further development, but must be regarded as qualitative rather than quantitative, and their limitations must be recognized [13].

The prospecting of geothermal fields makes it necessary to improve the techniques for more economic extraction of energy available in the thermal regions. The art of geothermal investigation is indeed of recent origin. The great advances achieved by prospecting techniques have been due not only to research, but also to practical experiments. The work of prospecting for geothermal fields must rely on methods as the key to success, just as in various branches of economic geology. This has to do with various well-known factors; money, time, knowledge, objectives and profits. Geothermal energy is one of the cheapest source of energy, but not a renewable resource. It is by no means easy to predict its life at full scale production. The only thing that can be said in this respect is that is indeed transitory [14].

Because each prospect in any geothermal exploration represents a unique combination of geological, hydrological, geochemical, geophysical, technical, and financial characteristics, no one exploration technique suffices for all situations. A given procedure may be informative in one area but not in another [15].

Early in the development of a new thermal area it would be highly desirable to estimate the total steam reserve of the field. This information is important both to encourage capital investment for financing further development and to determine the most efficient type and capacity of turbine-generator unit to be installed. Mainly due to the lack of knwoledge concerning the mechanics of steam reservoir, no satisfactory estimates of steam reserves have been made for any of the fields developed so far.

The customary method of calculating natural gas and petroleum reserves by plotting the decrease of reservoir pressure against cumulative production cannot be applied to steam reservoirs. This method can be applied to natural gas and oil fields because a specific volume of fluid exists in the reservoir at a specific initial pressure. Assuming a reservoir has constant volume, the fluid reserve at any stage of production will be related to the decrease in reservoir pressure caused by the withdrawal of fluid. It cannot be assumed, however, that a steam reservoir contains a fixed initial volume of fluid existing under static conditions.

It has been shown by a study of the variations in the deuterium and O^{18} concentrations in surface and hot spring waters that the majority of hot spring water is meteoric rather than magmatic in origin. It therefore must be assumed that the thermal fluid reservoir is not static, but rather consists of a large natural convective system. By study of the C^{12}, C^{13}, and C^{14} isotopes in the thermal systems at Steamboat Springs, Nevada, it has been further shown that the descending meteoric water spends at least 30,000 to 300,000 years underground, depending on the type of circulation.

In view of the evidence that thermal fluid reservoirs are actually dynamic circulatory systems of considerable capacity, the estimation of absolute steam reserves no longer has meaning. Instead, the problem involves not only estimating the amount of heat contained in the heat source but also the rate of heat flow from the source to the thermal fluid, and the rate of fluid flow through the circulatory system [18].

Generally speaking, it is essential to commence by delimiting the thermal area geographically, in accordance with the dictates of observation. Since there is already a certain amount of experience, and certainly bases for comparison with reference to what might be expected to occur in the subsoil, once we know that there is a certain set of conditions at the surface, we must proceed systematically to work directly on the surface.

Under these conditions one must plot surface isotherms, at 1 meter, at 2 meters, and, in general, at depths not requiring much work, and which can be accomplished with relative ease. From the readings of thermometers and thermocouples, the temperatures over $1^{\circ}C$ higher than the average for the formation, and those below an upper limit, for instance $50^{\circ}C$ above the average temperature of the formation, are detected. In this way the first thermal anomalies can be located.

The heat flux may next be estimated. By the aid of the following table, we get an idea of this parameter, according to the experience in the New Zealand geothermal fields [14].

Manifestation	Heat flux	Remarks
Abnormally high temperature gradient in the upper strata, unaccompanied by an important amount of steam.	Varies from 1 to 20 gm cal/sq m/s.	
Conductive and convective flux together.	From 4 to 200 gm cal/sq m/s.	
Convecitve flux. The area is characterized by visible steam, especially at high atmospheric humidity.	From 200 to 2,000 cal/sq m/s.	The greatest flux comes from light and thermally altered strato, from small fumaroles and, occasionally, from bubbling mud pools.
Large fumaroles with discharge vents 15 cm to 1 m in diameter, sometimes yielding slightly superheated steam.	Varies from 10^6 to 2×10^7 gm cal/sq m/s.	
Discharge of steam from hot ponds and bubbling mud pools.	Varies from 10^3 to 1.5×10^4 gm cal/sq m/s for calm water up to 1.5×10^6 gm sal/sq m/s for ponds in violent ebullition.	The principal discharge is in the form of steam.
Steam is discharge from hot springs and geysers. They may be quiet or active.	Of the same order of magnitude as above.	

In order to estimate the total amount of heat available in the source, it would be necessary to know its size, internal temperature gradients, and degree of crystallization. The rate of heat withdrawal from the source depends on the shape, structure and fluid content of the heat source; structure and permeability of the rock surrounding the source; and the thermal gradient within the circulating fluid and surrounding country rock. If this type of information has not been ascertained, a quantitative answer to the question of steam reserves cannot be given.

In a thermal system, such as at Wairakei, New Zealand, where heat coming from a magmetic source accumulates in a large aquifer, it is possible to estimate the amout of heat stored in the secondary reservoir. It has been calculated that the heat stored within 3000 feet of surface at Wairakei is 3.4×10^6 cal/sq cm (referred to 100°C). Over 80 percent of this energy, which was contained in 1.68×10^8 metric tons of steam and hot water, was withdrawn from the reservoir over a period of 8 years. During this period, the natural surface heat flow, as well as the temperature of the fluid in the producing wells, remained nearly constant. In order to evaluate steam reserves in a thermal system of this type, it is necessary to know whether heat is being produced mainly from the heat stored in the secondary reservoir, or whether the wells have tapped the channels feeding thermal fluid into the reservoir.

The geologic processes which control the life expectancy of a thermal field are extremely complex, and our understanding of them is still rudimentary. Nevertheless, it is necessary to investigate these processes to find the answers to the problems discussed in this study, as well as to evaluate the relative importance of geothermal power as a future energy source. From a more immediate point of view, however, it should

be remembered that a power installation is amortized over an average period of 20 years, an extremely short interval compared to the duration of the geological process related to natural geothermal activity [18].

All these problems will be solved eventually as more geothermal areas are explored by the drill and analyzed by geological, geophysical, geochemical and other testing methods. In most areas, some topographical, hydrological, meteorological, geological, geochemical, and geophysical information already exsits and should be thoroughly evaluated before new investigations are undertaken.

Major methods in geothermal prospecting are outlined in detail, in the following chapter.

1. Methods in geothermal prospecting

a. Geophysical

Geophysical prospecting may be defined as the art of detecting and interpreting anomalies in the local pattern of certain physical quantities, as measured by suitable sensing equipment and techniques. It is only to be expected that the presence of a geothermal field will affect or distort some of the local physical quantities, and geophysical aids have in fact proved to be of considerable value in the detection and interpretation of geothermal fields.

Geophysical work, however, should not be regarded in total isolation from other subjects, but proceed in close coordination with geology, hydrology, and geochemistry, so that physical measurements may constantly be interpreted and verified. For example, geochemisty can be used as a convenient physical instrument, like a

sophisticated thermometer or steam detector, being valuable both for planning and interpreting geophysical programs. The location of promising drilling sites is an act of complex detection that must eventually be checked by actual drilling. No single method of survey, geophysical, geochemical or geological, can be expected to yield a unique or unambiguous result, and the overall picture of a geothermal field and reservoir is built up by a continuous process of cooperative data synthesis and crosschecks [19].

Geophysics is drawn upon chiefly to define target areas for drilling. The existence of a geothermal reservoir can be inferred from the indirect measurement of various physical parameters at depth. These physical parameters include temperature, electrical conductivity, propagation velocity of elastic waves, density, and magnetic susceptibility. The most useful geophysical techniques for geothermal exploration are temperature or geothermal gradient surveys, heat flow determinations, electrical conductivity surveys, and passive-seismic methods such as microearthquake measurements or seismic noise detection. These methods can delimit the geothermal reservoirs and furnish data on subsurface thermal processes. Active-seismic, gravimetric, and magnetic surveys may prove justifiable in refining a regional geologic model, but they generally provide little useful information for defining the geothermal reservoir.

Determined by thermal techniques, average worldwide conductivity heat flow is about 1.5 cal/cm^2 sec. Heat flow slightly over normal can be due to exothermic chemical reactions, high content of radioactive materials, friction along faults, or migration of waters of different origins in areas of nearly normal geothermal gradient. Elevated heat flow owing to these phenomena are usually of restricted extent and of limited duration. Geothermal areas that are economically attractive under present conditions, however, can have heat flows that are up to several thousands times normal and

can persist for many thousands of years. Heat flows of such magnitude and duration are possible only where rocks of near-magmatic temperatures are nearby.

Although gradient measurements do define the areal extent of thermal anomalies, the prospector must be very cautious in extrapolating these gradients to depth. Two factors combine to ensure that a linear extrapolation will yield a high error rate. The first is the variation in conductivity of the rock with depth. In a sedimentary section, such as in the Imperial Valley of southern California, the proosity decreases strikingly with depth. Inasmuch as the thermal conductivity of minerals is 3 to 10 times that of water, the bulk conductivity therefore increases greatly with depth and decreasing proosity. Since heat flow is the product of gradient and thermal conductivity, the gradient must decrease with depth as the thermal conductivity increases. The second factor, convection, will have an even greater effect in reducing thermal gradients at depth.

When the mean thermal conductivity of the subsurface is essentially constant throughout the complex in which boreholes are drilled, the thermal gradients measured are obviously proportional to the heat flow values. The essential advantage of heat flow measurements, as opposed to purely gradient measurements, is that heat flow is independent of the in-situ thermal conductivity of each rock type. Therefore, in nonhomogenous terrains, only heat flow measurements enable us to obtain accurate information on the potentially productive zone [15].

In wide alluviated areas where bedrock geology is not exposed, it may be necessary to use geophysical techniques, such as

gravity, magnetic or seismic surveys to determine the geologic structure controlling the thermal system. The Salton Sea and Cerro Prieto geothermal fields in southern California and northern Mexico are examples of areas where these geophysical methods have been quite useful in delineating geological structure and in locating successful production wells. Most geothermal areas, however, occur in mountainous terrain where geologic structure and stratigraphy is well exposed, and geophysical surveys designed for the delineation of structure are unnecessary, at least in the early exploration stage. Later, after a discovery has been made, it may be desirable to make these surveys to investigate the deep structures underlying the reservoir and perhaps to identify buried magmatic heat sources [4].

Electrical and electromagnetic techniques in geothermal exploration measure electrical conductivity at depth. Temperature, porosity, salinity of interstitial fluids, and/or content of clays and zeolites tend to be higher within geothermal reservoirs than in surrounding ground. Consequently, the electircal conductivity in geothermal reservoirs is relatively high. There are a number of electrical and electromagnetic methods that measure electrical resistivity at dpeth. The telluric and magnetotelluric methods depend on measuring variation in natural electrical and electromagnetic fields. Several electrical techniques involve putting current into the ground at two electrodes and measuring the resultant potential at two other electrodes. The various electromagnetic methods involve the generation of magnetic field that varies with time, and the detection of either the electrical or the magnetic field arising from current induced in the earth.

Most of the published data on the use of electrical techniques in geothermal areas are from New Zealand, where experience over the past 10 years has indiciated that in the volcanic environment of the Taupo graben the most useful technique is de-resistivity profiling using linear arrays.

An electrical prospecting technique that is being incrasingly used in geothermal prospecting is the dipole - dipole array. This technique has been used to outline the Broadlands field, New Zealand, at depths of 1 to 3 kilimenters. Greater depths can be attained using very powerful sources and exceptionally well-grounded current electrodes. However, effective dipole - dipole investigations require complicated data analysis and careful interpretation, but the method is logistically simple and is insensitive to rugged topography.

Electromagnetic methods have been used in geothermal exploration only during the past six years. Although instrumentation and interpretation are complex, electromagnetic (inductuve) methods have two theoretical advantages over electrical methods: with an inductive method, signal size increases with decreasing resistivity, making measurements easier and more accurate in geothermal areas; and inductive methods are not adversely affected by near-surface high resistivity zones. These electromagnetic methods have been used to date in goethermal areas:

- a two-loop method used in New Zealand and Chile to investigate depths of 15-50 meters;
- an audio-grequency magnetotelluric method used in New Zealand, Nicaragua, Indonesia, and Kenya, which appeared to be an effective, rapid and easy reconnaissance tool; and
- an inductive method using a long wire source and a loop detector to investigate the Taupo volcanic zone to depths of 10 to 30 kilometers.

Passive seismic techniques. Many geothermal reservoirs are characterized by abundant microearthquakes and a relatively high level of seismic (background) noise. Accordingly, the precise location of microearthquakes and seismic noise may aid in delimiting fractured and permeable zones in geothermal areas.

Passive seismics involve recording local, naturally generated microearthquakes and thus determining faults that may be associated with geothermal system. The incidence of microearthquakes may be increased by the production of geothermal fluids or by injection of waste water, and monitoring of a field under development may be necessary [15].

In general, accurate locations of microearthquakes can be used to map at the depth active faults that may channel hot water to the surface. Focal depths in geothermal areas are unusually shallow: 2 to 6 km in Iceland, near surfact to 6 km in El Salvador, and near surface to 5 km in Japan, near surface to 5 km for the Geysers. Mapping of faults over such depth ranges may provide valuable information for selecting drilling sites. Microearthquakes may also give an indication of temperature at depth. Laboratory studies of fractional sliding on fractue surfaces in rocks suggest that the stick-slip process may be important in the generation of earthquakes. This mechanism has been shown to be dependent on temperature. Elevation of temperature may prevent stick slip and induce stable sliding [21].

Another passive seismic method, seismic noise or geothermal noise detection, records accoustic noise pattern within certain frequency ranges. Seismic noise measurements seem to provide a relatively simple method for detecting and mapping certain types of geothermal areas. Various studies suggest that there is an empirical relationship between reservoir depth, high temperature gradients, and high seismic noise level. If this relationship proves to be reliable, geothermal noise detection could be useful in future geothermal exploration, owing to the relative speed, mobility, and economy of the seismic technique [15].

Basically, the method is very simple. It consists of measuring the power spectrum of the vertical background noise in the survey area where the presence of a geothermal reservoir is indicated by a sharp increase in the noise level. To date, experimental evidence indicates that noise is most prominent in the frequency band of 0.5 to 5.0 kHz. The problems associated with the method are mainly the recognition and elimination of interfering energy from other sources, such as lakes, traffic, wind, earthquakes, etc. Another problem associated with the method is the well-known changes in noise level caused by variations in acoustic impedances of the near-surface material at the recording site [20].

In general, hydrothermal fields differ so greatly in character and environment that geophysical methods meet with varying success in

prospecting for steam or hot water. In some cases there is difficulty in applying geophysical techniques and in others there is difficulty in interpretation.

Owing to the permeability of the rocks, most New Zealand fields yield wet steam; little work has been done on dry steam fields. The permeability of the rocks also results in usable hot water often found by drilling close to the hot springs or fumaroles, so that much small-scale exploitation has been possible without the help of prospecting. Geophysics has been employed in mapping the limits of such fields, but its main uses have been in the study of the geological background, or in the attempt to penetrate beneath the shallow reservoir to locate deeper aquifers or feed channels.

Gravity surveys are primarily used to indicate the basement structure and are not very detailed, but minor positive anomalies have been found which probably indicate intrusive rocks genetically associated with the hot water. The basement rocks are only weakly magnetized, and magnetic surveys indicate the distribution of magnetic rocks within the overburden. Detailed surveys are valuable, since hydrothermal alteration converts the magnetite in the rocks to pyrite, thus weakening the magnetic field.

Resistivity surveys, designed to map the distribution of hot water at the water table, have been successful in uniform geological

conditions, but the interpretation is liable to be complicated by porosity and salinity variations. Deep penetration is hampered by the shielding effect of hot water near the surface.

Seismic refraction surveys have located cap rocks in some fields. Reflection work at Wairakei, New Zealand, showed very low seismic velocities, suggesting steam in the rocks instead of water and dry steam has since been tapped in this area. Seismic work in hydrothermal fields is handicapped by very high natural noise levels and energy dissipation [22].

Active seismic methods, gravity and magnetic surveys all fall under the category of <u>structural</u> or <u>indirect</u> methods, as applied to geothermal exploration. In contrast to the thermal, electrical, and electromagnetic methods described above, these structural methods do not study the properties of the hot fluids sought, but instead investigate the attitude and nature of the host rocks.

Active seismic methods involve the use of explosions to generate elastic waves. The reflection method utilizes energy reflected from subsurface interface between rocks of different physical properties. The refraction method utilizes seismic waves horizontally refracted along an interface and hence back to the surface. Both methods are used to determine subsurface structure, configuration and depth of basement rocks.

In general, magnetic surveys are probably the least useful geophysical tool in defining geothermal drilling targets. Positive magnetic anomalies can be related to very young intrusive and volcanic rocks associated with a geothermal system. In most areas, however, so many factors influence the character of a magnetic map that it is difficult to interpret them in terms of geothermal resources.

Surface and near-surface geophysical techniques serve primarily to site exploratory drill holes to depths of up to 3 km. The final phase of any geothermal exploration is the drilling of these exploratory wells, which provide the only way to determine actual geothermal reservoir characteristics and thus the only way to evaluate the potential for heat, power, minerals, mineral and fresh water. Data obtained from the drill holes ideally should include temperature-depth distribution, pressure-depth distribution, permeability, porosity, lithology and stratigraphy, and fluid composition. A full set of geophysical logs combined with production tests will provide the necessary data and allow evaluation of the site.

Information that can be obtained only from a borehole is essential in:

- estimating the ability of the geothermal reservoir to produce sufficient energy over a sufficiently long time to be economically attractive;

- distinguishing between different models of the geothermal system, with the aim of accurately predicting production characteristics under varying exploitation conditions, and
- calibrating and refining geophysical and geochemical methods for recognizing delimiting geothermal systems [15].

Magnetic measurements should not be used in preliminary exploitation. This is also true of gravity data, which principally apply to deep formations; they are costly and difficult to interpret.

Electric conductivity then proves to be the most valid parameter, because of the tectonics to be determined and because it is easy to operate. Moreover, electrical prospecting methods are inexpensive because electrical sounding in particular gives valuable data concerning the nature of the formations encountered. In addition, it is a versatile method offering the added advantage of indicating the warm areas through decreased formation resistivity by thermal effect [23].

Perhaps the most useful geophysical tool in outlining the area of the Broadlands, New Zealand geothermal reservoir at depth was the de-resistivily survey using a Wenner-array with spacing A = 550 m. Effective probing depth at this spacing is about 760 meters.

Dipole surveys were used in delimiting the Broadlands geothermal field at effective probing depths of 1.5 and 3.0 km. But the

analysis of the raw dipole data is complex and subject to considerable misinterpretation because of the boundary effects and because of the variation in effective probing depth with electrode spacing and orientation. Resistivity values determined from a dipole source located outside the field had to be reduced by 50 percent to agree with apparent resistivity measurements made with the source inside the geothermal field. The magnetic survey failed in its objective of outlining productive areas within the resistivity low.

As of 1971, eighteen wells had been drilled within the Broadlands resistivity low. Of these wells, all but one had measured temperatures greater than 270°C, with some having low production rates, owing to low formation permeability. Only one well has been drilled in the Broadlands region outside the resistivity low. This well, just outside the southwest resistivity boundary, had a maximum temperature of 244°C, but inadequate permeability [15].

b. Geochemical

Geochemical prospecting involves sampling and analyzing waters and gases from hot springs and fumaroles in the areas under investigation. The data obtained are then used to determine whether the geothermal system is hot-water or vapor-dominated in order to estimate the minimum temperature expected at depth, to estimate the homogeneity of water supply, to infer the chemical character of the waters at depth, and to determine the source of recharge water [15].

In the past ten years geochemical methods have been increasingly applied to evaluate various physiochemical parameters which are important feasibility functions inthe planning and operation of a geothermal development. Geochemical methods are now widely used in preliminary prospecting for potential geothermal exploration. Chemical data on natural discharge from thermal areas serve as an important guide for decision making on subsurface exploration by drilling. Chemical analysis of deep thermal fields provides information on flow patterns of water and assists in selecting improved drilling sites. During production, testing, and subsequent utilization, chemistry provides an efficient and inexpensive tool to detect minor and major changes in the reservoir, both with regard to temperature and water level fluctuation.

The wide applicability of geochemistry in all stages of geothermal exploration is especially important because of the relatively low cost involved as compared to geophysical surveys and subsurface investigations by drilling.

The usefulness of geochemistry in geothermal exploration was long obscured by a scholarly dispute about the origin of thermal water and the nature of its dissolved chemical elements. Most of the published studies centered on the question of magmatic or meteoric origin, and attempts were made to relate individual elements or components to some theoretical source. In the 1950's isotope studies showed that most of the water in thermal areas anywhere in the world could be directly

related to meteoric water. A small, but significant, amount of magmatic or juvenile water could not however, be excluded and the dispute presently continues.

In the 1960's an entirely new approach was initiated mainly emphasizing the fact that a geothermal area represents a chemical system at high temperature. The main components in this system are a fluid phase, the water, and a complicated, heterogenous solid phase, the wall rock. No matter what the origin of the heat or the individual chemical element in the system, reactions between the components would seek equilibrium at a relatively fast rate because of the high temperature. The chemistry of the thermal fluid could therefore not be interpreted in terms of a magmatic or other diffusely defined origin. The chemistry reflects rather a last state of equilibrium between the fluid and the solid phases of the system, and can be interpreted accordingly.

Many chemical analyses of thermal waters and gases have been published over the last decades, especially from those areas where economic interest has been involved.

Several reviews of chemical composition of thermal water have been made by various authors, classifying hot spring water into a few chemical types. The following table gives examples of the most important types of thermal water.

	1	2	3	4	5	6	7
SiO_2	501	640	456	412	322	109	60
Li	n.d.	14.2	n.d.	n.d.		n.d.	2.3
Na	250	1.320	5,025	609	75	2.0	129
K	25	225	905	51	11	3.0	69
Rb	n.d.	2.8	n.d.	n.d.		n.d.	
Cs	n.d.	2.5	n.d.	n.d.		n.d.	
Ca	0.9	17	354	14	263	2.2	272
Mg	0.0	0.03	23.4	4	73	0	68
F	9.5	8.3	1.5				2.4
Cl	127	2,260	8,730	878	1,490	15	170
Br	n.d.	6.0	n.d.				
I	n.d.	0.3	n.d.				
SO_4	108	36	28	262	3,730	758	501
As	n.d.	4.8	n.d.				
B	n.d.	28.8	131	4.4		6.9	4.3
NH_3	n.d.	0.15	n.d.	2		30	1.0
HCO_3	133	19	49				667
CO_3	70						
H_2S	0.2	—	—	—	216	—	2.6
pH	9.26	8.6	7.02	3.1	1.6	1.97	6.6
T °C	100		(220)	55	81	90	72

1. Great Geysir, Iceland; 2. Wairakei, New Zealand, Hole 44; 3. Ahuachapan, El Salvador. Drill hole (Magnesium value is obtained by complexometric titration and probably too high).; 4. Frying Pan Lake, Tarawera, New Zealand; 5. Yang Ming Shan, North of Taipai, Taiwan. 6. Norris Basin, Yellowstone Park, U.S.A.; 7. Mammoth, Yellowstone Park, U.S.A.

Note: 'n.d.' means 'not determined'.

<u>Sodium chloride water</u> is the most common type of thermal water in large underground reservoir systems. The pH is close to neutral at depth, but becomes slightly alkaline as water comes to the surface and loses steam and CO_2. The commonest anion is chloride and the ratio chloride/sulphate is high. Sodium is the principal cation. A relatively wide concentration range is found within this group.

Acid sulphate chloride water is a relatively rare type of thermal water. The acidity of the water is due to oxidation of sulphide to bisulphate at depth. As the waters rise to the surface and cool down, the pH shifts from neutral to acid because of changes to the temperature in the dissociation constant of bisulphate.

Acid sulphate water is common in fumarolic areas, where steam rising from a hot water reservoir condenses at the surface. H_2S contained in the steam is oxidized upon contact with air and also as a result of bacterial activity to form H_2SO_4. The water has a very low chloride content and may contain large and varying amounts of cations derived by acid leaching of small rocks. The springs containing this type of water usually have little or no discharge, and often the water carries much suspended clay material.

Calcium bicarbonate water occurs commonly at low temperature travertine depositing springs. Water of this kind has not been found at economically feasible temperatures, and the calcite precipitation is a severe drawback in utilization.

In general, more than one type of thermal water can occur within the same geothermal system. An important aspect of hydrothermal chemistry is to find a logical relationship between the different types of water within the thermal area, and especially to show how the chemistry of hot spring water can be used for predicting the chemical composition

of thermal waters at depth, and the physical environment of the water in the geothermal reservoir.

The thermal gases form another set of chemical groups. The same type of thermal gas may appear with two or more distinct types of thermal waters. Three main types of thermal gases can be defined:

- gases characterized by very high N_2 and little or no active gases,
- gases with very high CO_2, but minimal H_2S and H_2, and,
- gases with high H_2 and H_2S, but CO_2 also as a maior constituent.

A continuous gradation exists between the last two groups of gases and even to some extent between all groups.

The table below gives an example of chemical analyses of the most common types of thermal gases from a few major geothermal areas.

	1	2	3	4	5	6
CO_2	0.0	92.2	91.0	86.7	67.0	63.5
H_2S	0.0	4.2	2.6	4.1	7.3	1.69
H_2	0.01	1.8	2.0	2.6	23.7	14.67
CH_4	0.04	0.9	0.03	0.3	0.2	15.29
N_2	97.1					
Ar	2.07	0.3	4.43	6.3	1.4	3.53
O_2	0.0	—	0.0	0.0	0.0	
NH_3	—	0.6	—	—	—	1.28
H_3BO_3	—	0.05	—	—	—	0.14

1. Reykjavik, Iceland. Drillhole; 2. Wairakei, New Zealand, Drillhole: 3. Hengill, Hverakjalki, Iceland. Steam vent. 4. Hengill, Hveragerdi, Iceland. Drillhole. 5. Hengill, Nesjavellir. Drillhole. 6. "The Geysers", California, U.S.A.

One of the most important contributions to our present knowledge of geothermal systems was the recognition of the meteoric origin of thermal waters. Several scientists studied the isotopic ratios H/D and O^{16}/O^{18} in geothermal waters from widely separated areas and compared these with the isotopic composition of meteoric waters in the corresponding areas. The H/D values for the geothermal waters coincide exactly in each case with the H/D values for the meteoric waters, but the O^{16}/O^{18} values are offset due to exchange of oxygen isotopes in the geothermal water with oxygen of the wall rocks in water channels. These results finally settled the dispute about the volcanic or "juvenile" character of geothermal waters, but there is indication that a small amount (5-10%) of water other than meteoric in origin could not be excluded. A possible interpretation of the origin of dissolved components in the geothermal water may then be of volcanic origin, injected into the main body of meteoric water as a high density steam carrying large amounts of dissolved solids.

Various papers show that a large part of dissolved solids in geothermal waters can be explained on the basis of reactions between water and wall rock of permeable channels in the geothermal reservoir. Two types of reaction can be defined: reaction where a temperature-dependent solution equilibrium is established between water and minerals of the wall rock, and a leaching of elements reaction not accomodated in the structure of stable mineral phases at the physiochemical conditions in the reservoir. From two simple rules it is possible to predict two

major characteristic features which should be common to all deep circulating geothermal waters:

- all elements governed by solution equilibrium should be in approximately equal amounts in all geothermal waters, and the range in composition should be in accordance with variation in temperature,
- all elements leached from wall rocks, and which do not precipitate in secondary mineral phases, should show large spread in values between individual geothermal areas.

The discharge of chemical elements from a geothermal area integrated over its lifetime, would give quantitative limits to the theory that all dissolved solids are derived from wall rock leaching. There were attempts to estimate the annual requirement of rock volume to provide some of the ions in the chemical output of Wairakei, New Zealand. For the minor elements, Cl, B, F, Li, Cs, and As, 0.02 to 0.0001 km^3 of rhyolite were needed per year, and the heat flow from the area was maintained by the crystallization of 0.01 km^3/year of magma. It has been assumed that the age of the Wairakei area is about 500,000 years and the volume of rhyolite, which has been totally leached with regard to some of the above elements, would be 2500 to 5000 km^3 if the rate of the chemical flow has been the same over the entire lifetime of the system. Since the rock porosity is probably about 10%, the total affected rock volume would have to be much greater. It has been suggested, on the basis of carbon isotope data, that water circulation times are between 30,000 and 300,000 years in Steamboat Springs, Nevada. Considering

such a slow water movement the throughput of water during the lifetime of the geothermal system would be only a few successive fillings of the reservoir [55].

Chloride analyses can be used to discriminate between hot-water and vapor-dominated geothermal systems. Chloride contents in excess of 50 ppm characterize most high-temperature, hot-water systems, whereas springs associated with vapor-dominated systems consistently display chloride contents less than 20 ppm.

Several constituents or ratios of constituents can be used to estimate minimum reservoir temperatures of hot-water geothermal systems. These include SiO_2 content, Na-K-Ca relationships, $Cl/(HCO_3 + CO_3)$ ratio, Cl/F ratio, and Mg content. Of these, SiO_2 content and the relationship between Na, K, and Ca have been quantified to yield numerical estimates of reservoir temperature.

Measurement of the isotopic composition of hydrogen and oxygen in waters serves to specify the origin of the water and to evaluate the hydrology of the region. For example, studies in the Imperial Valley demonstrated that most of the geothermal water in the central and southern parts of the Salton Trough was derived from the Colorado River underflow, whereas the geothermal fluids of the Salton Sea geothermal field were derived from runoff from the nearby Chocolate Mountains [15].

A rapid geochemical survey can cheaply reveal much about the potential of a geothermal area. Dry steam is unlikely in an area where springs contain appreciable chloride (over 20 ppm). An abundance of acid sulfate springs which are near boiling in temperature but low in discharge, favors the possibility for dry steam at depth. However, chloride waters in the surrounding area are an unfavorable indication because local acid sulfate springs may also result from the boiling of chloride waters at depth.

An area containing boiling springs with appreciable sodium chloride and relatively high ratios of K/Na and Li/Na is likely to have a notable temperature increase with depth, at least within a hundred feet or so of the surface. Diluted neutral or alkaline spring waters, even if moderately high in temperature at the surface, are not likely to have notably higher temperatures at depth. Springs with chemical compositions similar to ordinary meteoric water almost certainly do not have a volcanic component. Temperatures near those of magma are highly unlikely in the vicinity, and thermal gradients cannot be high for long periods of time adjacent to conduits carrying such waters.

There are potential problems of deposition and corrosion, as some thermal waters percipitate large quantities of $CaCO_3$ when discharged naturally at the surface. Other thermal waters precipitate little or no $CaCO_3$ during natural discharge. But when they are erupted rapidly from high temperature and pressure, much CO_3 is selectively

lost to the vapor, carbonate equilibrium is shifted and the HCO_3 dissolved in the water is converted to CO_3 which in turn results in deposition of $CaCO_3$ in the wells. At Steamboat Springs, Colorado, continuously erupting wells may fill with $CaCO_3$ within 4 days to 4 months or more. The wells are then shut down and cleaned by drilling out the deposits.

Thermal areas characterized by natural carbonate deposits are likely to have particularly serious problems in erupting wells. An occasional shut-down for removal of deposit is not necessarily serious, but frequent shut-downs with resultant low average production cannot be tolerated in many areas. Carbonate-depositing waters can probably be utilized by producing the water under pressure and removing the heat by heat exchangers.

A few thermal spring waters are exceptionally high in SiO_2 in the remaining water. The solubility of amorphous silica in spring waters is about 350 ppm at 100°C, and is probably about 500 ppm at 150°C. Waters that are very high in silica when erupted may precipitate silica in pipes.

Some thermal spring areas are very acidic near the surface and condensates of gases that are high in free CO_2 and H_2S are corrosive. Problems, concerning the external and internal corrosion of pipes which have already been encountered in explored thermal regions of Italy, New Zealand, and elsewhere, apparently have been solved without great difficulty [11].

Silica and the alkali ions are probably the best indicators of near surface changes due to precipitation and ion exchange with wall rocks. Thermal water leaving a reservoir at 250°C and appearing at the surface at 100°C is highly supersaturated with silica, because of both convective heat loss and direct concentration and cooling by boiling of about 20% steam. Very often the water will approach the surface by a defined channel, or channels, that may become dispersed along horizontal near-surface layers, and flow out on the surface in several boiling springs. Silica precipitation will proceed proportionally to flow a distance from the main upflow channels, and this will be reflected in the silica concentration of the spring [55].

Geochemistry has an important role in solving various problems connected with geothermal resource development, such as evaluation of reservoir energy reserve, reservoir depletion, power plant design, corrosion, scale formation, and effluent disposal. The following chemical indicators of subsurface temperatures in hot water systems is in broad use for evaluating reservoir potential [39].

Indicator	Comments
1) SiO_2 content	Best of indicators; assumes quartz equilibrium at high temperature with no dilution or precipitation after cooling.
2) Na/K	Generally significant for ratios between 20/1 to 8/1 and for some systems outside these limits.
3) Ca and HCO_3 contents	Qualitatively useful for near-neutral waters; solubility of $CaCO_3$ inversely related to subsurface temperatures.
4) Mg; Mg/Ca	Low values indicate high subsurface temperature, and vice versa.
5) Cl dilution	Assumes dilution of lower-Cl springs by cold water, permitting calculation of subsurface temperatures from required mixing ratios with highest Cl waters.

6) Na/Ca	High ratios may indicate high temperatures but not for high-Ca brines; less direct than 3?
7) Cl/HCO_2+CO_3	Highest ratios in related waters indicate highest subsurface temperatures and vice versa.
8) Cl/F	High ratios may indicate high temperatures but Ca content (as controlled by pH and CO_3^{2} -- contents) prevents quantitative application.
9) H_2/other gases	High ratios qualitatively indicate high temperatures.
10) Sinter deposits	Reliable indicator of subsurface temperatures (now of formerly) > 180°C.
11) Travertine deposits	Strong indicator of low subsurface temperatures unless bicarbonate waters have contacted limestone after cooling.

In general, the relationship between hot spring chemistry and reservoir temperature is of primary interest. Those elements in geothermal water which are governed by temperature-dependent solutions equilibria can be used to estimate the subsurface temperature. These are principally silica, magnesium, and the ratio between sodium and potassium.

Fig. 6 shows the solubility of quartz and amorphous silica in water. Silica in waters obtained at different temperatures in hydrothermal experiments with common rock types are also reproduced in the diagrams. Obviously it is not easy in any single case to select with certainty the appropriate curve, but the possibilities can be considerably narrowed. Studies of hydrothermal alteration is explored geothermal areas have shown that quartz is always an important secondary mineral phase at relatively shallow depth. In most cases one would therefore compare the silica value of the spring water with the quartz solubility curve. This is done assuming that silica remains metastably in solution through the temperature gradient

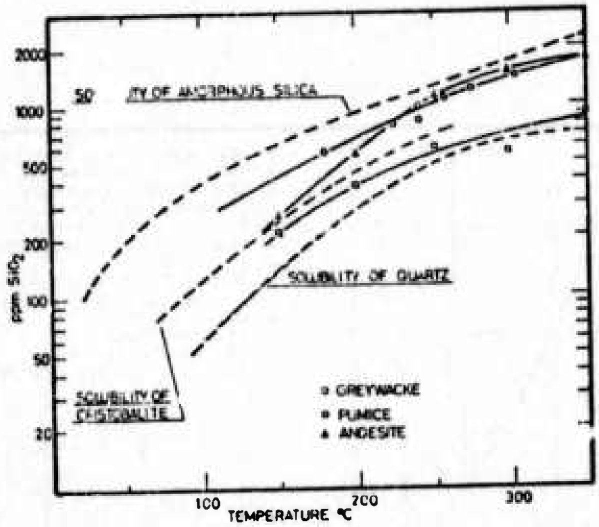

Fig. 6. Solubility of various modifications of silica and common rock types [55].

from the reservoir to the surface. This may actually be so if the speed and volume of water is considerable, but reliable estimates of temperature by the silica method cannot be expected from springs with low discharge. Any precipitation of silica on the way to the surface would result in low temperature values. Higher values, on the other hand, would result if additional silica were dissolved from the wall rock at depths above the zone of quartz precipitation. The silica value of the water might then approach the solubility for amorphous silica. The silica thermometer should therefore be used with caution when dealing with surface springs, especially when the spring has a low discharge or is a minor seepage.

The atomic ratio of sodium to potassium is another indicator of reservoir temperature. This ratio is governed by a complicated equilibrium involving alkalifeldspars and K-mica.

Fig. 7 shows the atomic ratio for Na and K at respective $T^{o}C$ diagram which in the higer temperature range is based on experimental data, but in the lower temperature range the chemical data are based on drill hole discharges with known down-hole temperatures. Essentially the same

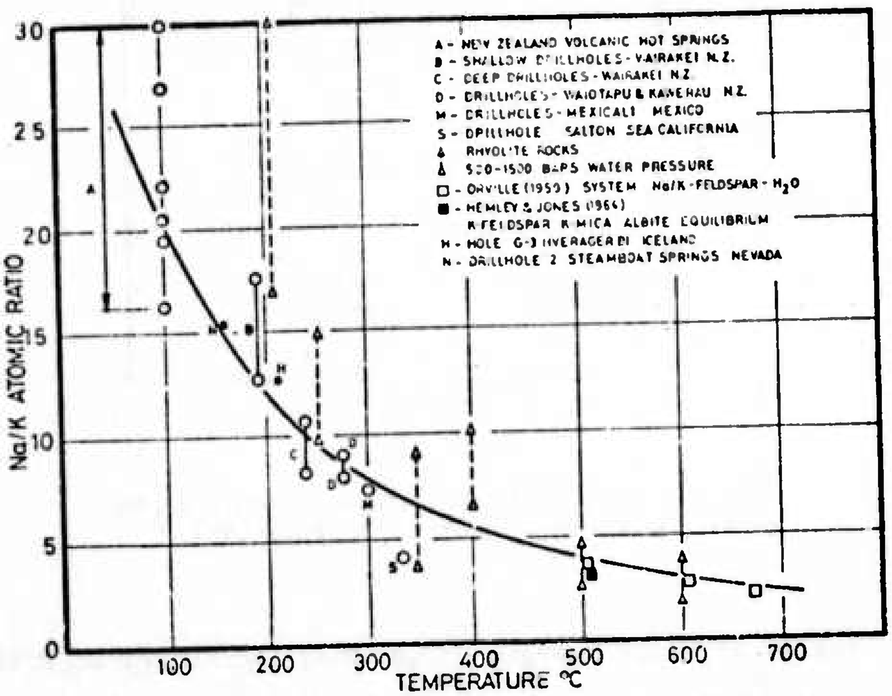

Fig. 7. Atomic ratio Na/K for thermal waters from various sources and experimental reaction solutions [55].

cautionary remarks apply to the use of the Na/K atomic ratio for surface hot springs as for the silica equilibrium concentrations. Na and K take longer to establish than the SiO_2 equilibrium, which would give a longer metastable persistence of the Na/K ratio. On the other hand potassium is preferentially absorbed on the surface of hydrothermal clay minerals such as montmorillonite. This mineral, and the closely related, mixed layer structures montmorilloniteillet and chlorite-vermiculite, are common the upper few hundred meters of geothermal areas and potassium uptake into these minerals may affect the Na/K ratio.

Solubility curves for magnesium in secondary minerals have not been determined, but hydrothermal experiments show that magnesium is preferentially incorporated in clay minerals which are stable at high temperature, such as chlorite. As a result, water which has been above 200°C in

contact with altered rocks is highly depleted in magnesium, the Mg concentration seldom exceeding 1 ppm. Magnesium does not therefore give a well defined temperature value, but its absence indicates reservoir temperatures which are economically feasible.

All of these temperature indicators, as well as other elements in the hot spring waters, may show more or less regular gradation within a group of hot springs. Chemical gradation can reveal important information on shallow subsurface flow patterns of thermal water and the location of zones of major upflow. Furthermore, they will assist in judging which particular hot spring within a given area comes closest to showing major factors in the chemistry of the reservoir fluid.

Fumarolic or steam fields with little or no discharge offer fewer possibilities for chemical prospecting than do the hot spring areas. The steam is often associated with some H_2S which tends to oxidize near the surface into sulfuric acid. The acid attacks the surrounding rocks and turns them into soft clays, usually containing kaolinite, opal and some sulphates. The zone of acid alteration extends down to the ground water level where an abrupt change to alkaline condition occurs, resulting in totally different mineral assemblage. The condensation water which accumulates in the steam pits is diluted with meteoric water, depending on the amount of precipitation in the area. The chemistry of the steam field water therefore does not have a direct relation to an underground reservoir of geothermal water, except in regard to volatile components. The water has a pH value ranging down to 0.5 or less, and due to its chemical aggressiveness it often contains large amounts of various elements which for the most part are derived from the surrounding rocks.

The volatile components do not provide direct information on the reservoir temperature since little is known about the relative amounts of volatiles in relation to temperature. Empirical evidence does, however, indicate that the presence of hydrogen in the fumarole gases is associated with temperatures in excess of 200°C.

High nitrogen gases (> 90% N_2) are never associated with fumarolic activity, but gases consisting principally of CO_2 may be associated with both low temperature calcium bicarbonate springs and high temperature fields. The most common gas composition in fumarolic fields is CO_2, H_2S, and H_2 in various proportions. A survey of gas chemistry in individual steam vents within a fumarolic area may indicate a gradation which can be related to the reaction of individual components with wall rocks in shallow layers. Assuming progressive differentiation from the source to the surface, the chemical variations may indicate the area of major underground flashing; H_2S is probably the most sensitive indicator in this respect. Apart from the empirically proven association of the CO_2-H_2S-H_2 gas mixture with higher underground temperature, the detailed interpretation of gas analyses from natural fumaroles is difficult and should be done with due regard to external conditions and the sampling technique since small variations in these factors may cause a large spread in relative amounts of analysed components.

Volatile components such as ammonia and boric acid are present in some fumarole discharges, and become concentrated in the condensed water. Because of the relatively low volatility of boric acid and high reactivity of ammonia with near surface clay material, these components are not carried long distances in the steam phase. Where these components are present they may therefore show concentration gradient within the area which would indicate the zone of most intense subsurface boiling.

Important factors in the operation of geothermal power plants are the amount of noncondensible gases associated with steam, and the possibility of precipitation of solid substances in pipes. The amount of total gases in deep hot water varies within wide limits in different geothermal areas. In Hveragerdi, Iceland, it is 0.003 mole percent, 0.02 mole percent in Wairakei, New Zealand, and 0.07 mole percent in the Mexicali field.

An exact figure on the gas/water ratio cannot be obtained except by sampling steam and water from a producing drill hole. Some indications can be obtained from measurements of gas/water ratios in fumaroles or steam vents, but here the separation temperature is not known and gases may be lost by reaction with wall rock or absorption in shallow ground water. The pH of the drill hole sample is different from the deep water sample due to concentration of the sample by boiling, loss of CO_2 and H_2S, and possibly by oxidation at the surface. All components, both water/steam and noncondensible gases, must be sampled and analyzed at a known pressure. The results are subsequently computed back to a one-phase system at the known reservoir temperature. The drill hole must therefore draw its production from a liquid phase only, which can be verified by comparison of the directly measured drill hole temperature with the enthalpy of discharge.

The most significant pH-buffering systems are carbon-dioxide-bicarbonate and silica-silicate, but other weak acid-base equilibria must be considered, such as hydrogen sulphide-bisulphide, boric acid-borate, ammonium-ammonia, etc.

If the changes occurring in the hydrogen ion concentration are known upon flashing of the water, it is possible to predict the possibilities of calcium-carbonate precipitation. This is an important factor in feasibility studies for power plants, since scaling calls for periodical clean-out operations. In several cases calcite may precipitate in the formation outside the drill hole and block feeding fissures. The drill hole is then damaged beyond repair. This can be controlled to some extent by pressure regulation at the valve, bringing the boiling into the hole.

Precipitation of silica upon flashing of the geothermal water seems to provide less trouble than calcite precipitation. Several scientists studied the behavior of silica in hot spring waters and found that dissolved silica would polymerize quickly upon cooling, but stay in solution without precipitation for some time. Hot spring waters containing less than 200 ppm SiO_2 usually do not form sinter deposits.

Containers for sampling of geothermal fluids should preferably be made of polyethylene, since glass bottles could alter the silica and alkali content of the sample. If trace metals are to be determined in the water the sample container either absorbs the metal ions or contaminates the sample. Bicarbonate and pH are preferably determined in the field, but special samples are commonly taken into pressure sealed glass bottles for later analysis. Other volatile components, such as H_2S and ammonia are fixed chemically in the field. Silica is usually determined colorimetrically with ammonium molybdate, but in supersaturated solutions silica tends to form polymers, which do not react with the molybdate. The sample aliquote is therefore digested with sodium hydroxide before analysis. Magnesium in low concentration is difficult to determine with the conventional EDTA* complexometric titration, which usually results in high values. Because of the importance of magnesium as an indicator of high temperature, it is necessary to have an exact determination of this element. Atomic absorption spectometry is probably the most reliable method. In order to obtain meaningful values for the proportions of different weak acid-bases for calculation of underground pH, the alkalinity titration is performed after a method of Ellis and Ritchie (1961) which differentiates between the different carbonate species and the so-called "effective bicarbonate", which is a measure of total alkalinity. The preceeding data are only a few significant points for analytical procedure and sampling methods [55].

The conclusions to be drawn from the examples discussed in the precceding paragraph is that no single criterion or rule can be followed in selecting promising thermal areas for further prospecting. Each area must be considered individually, and valid conclusions can only be reached only by evaluating all relevant data within the framework of the total geologic environment [4].

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* EDTA - Ethylenediaminetetraacetic acid

c. Geological and hydrological

Field work should begin with regional geological and hydrological surveys in order to geographically delimit the geothermal area. The geological survey therefore should emphasize the tectonic and stratigraphic setting of the area, recent faulting, the distribution and age of young volcanic rocks, and the location and character of thermal manifestations, including hydrothermally altered rock. The hydrological reconnaissance should include temperature and discharge measurements of hot and cold springs, chemical analysis of the springs, determination of the water table in available wells, and evaluation of surface and ground water movement. However, basic meteorological data (temperature, humidity, precipitation, etc.) should not be neglected, for these data are important in the planning of geophysical and drilling programs. As geothermal prospects are identified, these regional studies are gradually transformed into detailed studies around potential drilling targets, with the aim of predicting the geological and hydrological conditions encountered at depth. From the geological and hydrological observations, one should develop a realistic structural, stratigraphic, petrologic, and hydrologic model to serve as a guide to further exploration and development [15].

Geological mapping of rocks exposed at the surface provides three types of practical information for exploring a geothermal area:

- the kinds and physical properties of rocks that may be encountered at depth,

- the recognition of the structural control of migrating thermal fluids. In tight rocks such as granite, impure sandstone and shale, the channels of migration of thermal water are faults, fractures, or any relatively more permeable strata, and

• geological mapping resolves the history of an area and gives some key to the length of time a system has been active, as well as some information on the probable magnitude of the heat source [11].

A geological map of the area should be made to a scale of about 1: 25,000 and should cover a sufficiently large area to show the relationship of regional structure to smaller secondary structures which might control the location of the surface manifestations. The overall objective of making the geological map is to obtain a three-dimensional picture of the structure and stratigraphy of the area. In making the geological map, particular attention must be given to determine the geological control of the spring system, indicate permeable horizons or structures which could be good production zones, and identify possible impermeable capping horizons [4].

In general, detailed geological mapping will extend well beyond the limits of the hydrothermal field and this will be assisted by geophysical surveys, designed to clarify the structure, rock sequence and hydrology. Gravity and aeromagnetic work may be used to build up the broad picture, and seismic profiles may be used to provide local detail. Electrical surveys may be used to map the distribution of hot or saline water, and surface magnetic surveys may be used to show those areas which have been subjected to hydrothermal alteration [16].

As part of the surface reconnaissance, it should not be ignored that vegetation may be an indicator of thermal areas, since a certain type of vegetation is characteristically modified by various temperatures [14].

For the efficient performance of this stage of mapping work it is very desirable to have good topographic maps available, on a scale of 1:100,000 or larger and a set of recent stereoscopic aerial photographs on a scale of 1:10,000 for survey planning and positional control.

At the outset of all field work it is important to set up a geodetic survey network and a system of benchmarks at a sufficient number of points to allow all maps resulting from the survey to be related to a common grid. Also it is very helpful in correlating collected data to have all maps either on the same scale or on the smallest possible number of different scales [19].

d. Airborne

Airborne infrared sensing equipment is a relatively recent development in geothermal prospecting. Multiband photography (visible and infrared spectrum) and microwave radiometry are used to depict the anomalous spectral reflectance associated with hydrothermal alteration zones. The data obtained are correlated with ground control through detailed thermometric, gravimetric, and subsurface heat flow mapping. There are some factors influencing the quality of infrared records, such as solar radiation, diurnal variation of surface temperature, wind, fog or condensation, degree of emissivity, flight altitude, ground velocity and instrument characteristics. Direct measurements of temperature made on the ground are more accurate, but the airborne infrared method promises to be useful in reconnaissance surveys to detect large thermal anomalies within arid, unexplored, or inaccessible areas [60].

The infrared scanners normally operate in the 1.8 to 5.3 micron or 7.5 to 14 micron transmission windows in the atmosphere. Presently thermal infrared imagery is a noise limited system. Most of the thermal annomalies on the imagery are the results of outcrop, slope direction and magnitude, soil moisture, difference in rock properties, vegetation, etc. Presently, heat flux anomalies less than about 100 to 150 times normal cannot be accurately detected with thermal infrared techniques [15, 56].

Normal and infrared color photographs on the same scale can be useful for outling possible hot areas in the office before proceeding to the field. If the field is situated close to large bodies of water or on the banks

of a river, long wave infrared scanner images of the area may be of value for mapping hot water seepage as well as the areas of intense ground surface activity. Recent experimental work shows that areas having a heat discharge of about 350 μcal/cm^{2}s (roughly 230 times normal) and higher can be identified with reasonable certainty. However, it is usually possible to map heat flow anomalies down to much lower levels by shallow surface thermometry, and a special aerial infrared survey would be justified only in exceptional cases. Preferably, surveys of this kind are best undertaken at the same time as other aerial mapping and photographic projects [19].

It should be kept in mind, however, that the data resulting from this method, as well as the information from shallow resistivity observations and shallow temperature probes, can be greatly affected by near-surface geologic and hydrologic conditions, and may therefore have little bearing on the deep thermal system which is the real exploration target. For example, relatively high thermal gradients may be found by shallow temperature probes in impermeable strata overlying a thermal aquifer, but the same gradient could be measured over a shallow aquifer containing only moderately warm water as over a deeper aquifer containing much hotter water. Obviously, this method alone should not be used indiscriminately for choosing well sites, but should be used only in conjunction with another method which can determine the depth of the reservoir under investigation.

However, aerial photography (particularly color and color infrared), thermal infrared imagery, and radar imagery can be considerably useful in defining active faults that may be potential drilling targets [15].

The aerial infrared photograph have been extensively used by the Soviets in studying various geothermal anomalies, such as geysers, fumaroles, thermal springs and streams, mud volcanos, and thermal areas of Kamchatka [56]. Aerial surveys of volcanic areas on Kamchatka, has also been conducted by polarization and spectral methods. The survey was made at altitudes up to 1 km with standard solar illumination aboard an AN-2 aircraft. An ASP-15 spectrograph was used to obtain three spectral character-

istics: total radiation intensity, degree of polarization and orientation of the polarization plane, using spectral range of 400-67 mμ. The use of an infrared spectrometer assembled on the basis of a ZMR-2 instrument made it possible to study the brightness distribution of solar light in the spectrum which was reflected from volcanic areas in the spectral range from 0.3 to 2.5μ [57].

Satellite imagery studies have proven to be valuable supplementary tools for the mineral and petroleum industries. Analyses of satellite imagery have been conducted to evaluate regional aspects of mineral deposits as well as to map structural and lithologic detail. Data derived from these studies have been used to facilitate the planning of ground geologic surveys, geophysical field explorations, and drilling programs. Much of the methodology and many of the techniques developed for interpreting space imagery for mineral exploration are applicable to geothermal resources exploration using satellite data.

The main characteristic and principal advantage of satellite imagery is the synoptic coverage of large areas. This overview, obtained with uniform lighting conditions, sacrifices some ground resolution, but synoptic coverage allows regional structure-tectonic relationships and their significance to potential resources to be evaluated on a single image.

A second characteristic of satellite imagery is the extremely high altitude which eliminates cultural details. It can confuse or obscure the surface geological picture and an accentuation of subtle surface anomalies that may be significant to potential geothermal resources.

Because of these two characteristics, satellite imagery can be used by the geothermal researchers for regional structural studies, detection of favorable lithologies, and soil and vegetation anomalies. Careful studies of space imagery reveal that many geological characteristics distinctly appear on imagery as do anomalous areas probably associated with

geochemical and geophysical changes near a geothermal system. Even without surface manifestations such as springs and fumaroles, image analysis supplies indirect evidence suggesting areas with high probability of geothermal potential.

Remote sensing techniques for exploration of geothermal and other resources are being developed and used at many different levels and will undoubtedly continue to offer many possibilities for application in all phases of research, exploration, and development [147].

2. Stimulation of geothermal systems

Although all geothermal anomalies involve the concentration of heat, naturally productive geothermal systems require the circulation of water. This water serves as the means by which heat is transferred from a deep igneous heat source to a geothermal reservoir shallow enough to be tapped by drill holes, and as the means by which heat is transferred from rock to a well and hence to the surface. Accordingly, naturally productive geothermal systems must have adequate porosity and permeability. If either of these factors is inadequate, the geothermal system will require artificial stimulation by hydrofracturing, explosions, thermal cracking, or other methods discussed in this subchapter. Reinjection of the produced fluids or of surface fluids may also be necessary [15].

Stimulation of geothermal dry-steam and hot-water systems. Although dry steam geothermal systems are not abundant, they produce electricity more efficiently than other geothermal systems. Production problems are relatively minor, and the discovery of vapor-dominated systems comparable to that at the Geysers would lead to rapid development and production. But both the Larderello and the Geysers dry steam fields have experienced a decline in steam pressure from producing wells through the years. Reinjection of condensate from the turbine exhausts, already in practice at the Geysers, or the injection of surface waters into the system

should retard depletion, but for a variety of reasons production can be expected to decline with time. It is difficult to estimate how effective the stimulation of dry-steam systems might be, but it is reasonable to assume that a geothermal well that is known to produce but has declined to sub-economic levels may undergo stimulation by techniques similar to those in use for gas and oil wells. Thus, studies and field experiments to determine appropriate stimulation techniques need to be undertaken.

The greater abundance of hot-water systems over dry-steam systems suggests the need for a correspondingly greater research and development effort, although they pose more serious development and utilization problems. For example, since superheated water flashed at the surface results in only about 10 to 20 percent of useable steam, it is evident that means should be found to extract heat from the formation rock, as well. The use of low-yield nuclear explosives to create an artificial geothermal fluid reservoir in natural aquifers offers the greatest promise for improved exploitation of this resource.

Stimulation of dry geothermal systems. The development and production problems dependant upon the use of dry, hot geological formations are even less known than those encountered with low temperature geothermal aquifers. The stimulation of geothermal resources has been under consideration since the early speculations by Carlson (1959) and Kennedy (1964), and several techniques of stimulation methods have since been proposed.

One method proposes using injected water to produce steam from dry, hot geothermal deposits previously fractured by a suitable array of multiple large-yield nuclear explosives. Various studies analyzed detonation configurations yielding an optimum volume of fractured rock for the extraction of heat from a closed-loop cycle of surface water.

Smith et al [66] proposed using hydraulic thermal-stress fracturing for the stimulation of geothermal formations having insufficient natural permeability. Cold surface waters would be used to pressurize natural

or stimulated fractures; the resulting shrinkage of the rock would cause additional cracks, perhaps sufficient enough to propagate increase permeability over an extensive volume of the formation. A second hole would then be drilled to intersect the upper reaches of the hydraulically fractured region. The cold water initially pumped into the deeper well would establish closed-loop circulation through the cracked zone into the new, higher well, and a vapor-turbine cycle at the surface would be used to produce electricity [58].

However, the use of explosives or hydrofracturing techniques to alleviate these production problems has not been explored very much. Some attempts to hydrofracturing have met with little success due to the relatively high permeability of even the "plugged" formations. Also, it is very difficult to obtain pumps with sufficient capacity and head to produce adequate hydrofracture pressures at the bottom of the well. High explosives in liquid or slurry form are not generally stable at typical well conditions of high temperature and steam saturation. A further problem is the limitation of quantities of "canned" explosives which can fit inside the 14 inch well casing. To produce significant results, large yields will probably be required. The possibility exists that a small nuclear device 1/2 to 5 kt (equivalent to 500 to 5000 tons of TNT) would produce significant results [68].

Several variations of the hydraulic fracturing procedures have been suggested, including:

- hydraulic fracturing from the bottom of the first hole, to ensure communication between this point and the crack system established by previous fracturing at a high level;

- hydraulic fracturing simultaneously from two holes; and

- hydraulic fracturing from an open (uncased) section at the bottom of the first hole.

Selection among these and other possibilities must await more detailed analysis, and agreement among drilling and hydraulic fracturing specialists [66].

A large-scale hydraulic fracturing experiment to free currently unrecoverable natural gas is being set up in Colorado by CER Geonuclear Corp. The government-industry sponsored program is designed to get production data for comparing a large-scale nonnuclear technique with nuclear stimulation. The project site is within a mile of Project Rio Blanco nuclear experiment. It is hoped that this experiment will provide additional data for geothermal stimulation by hydraulic fracturing [72].

Increased formation permeability might also be achieved by the use of small-charge, properly spaced, high energy chemical explosives.

Stimulation of a geothermal well with chemical explosives differs from conventional water well or hydrocarbon well stimulation. The significant variables can be lumped into three areas: host rock type, fluid temperatures, and fluid composition. Stimulation method selection must be matched to host rock conditions and may be: borehole (wetted perimeter) enlargement by springing, i.e., material removal, host compaction, fracturing, perforation (gun or jet), or porosity/permeability modification by breakup of mineral deposits blocking fractures or pore spaces or explosively driven "sand" fracturing fluids.

For example, an attempt to shatter a zone of chlorite and clay using a heavy, brissant charge would lead to no stimulation or even a lessening of production, but the same approach would be ideal for opal blocked fractures in an unaltered crystalline host rock.

The temperature environment in the borehole affects the choice of explosive, booster, and detonator, which affects the selection of stimulation methodology. Therefore, a highly brissant explosive, ideal for

fracturing may prove less brissant at elevated temperatures, and present a handling problem such as rapid melting, or the explosive system may "cook off" prematurely. Most geothermal wells are located in the areas of natural surface fluid leakage and are intimately involved with near-surface ground water where the epithermal temperature range between 50 and 200°C. A few wells have tapped mesothermal fluids (200 to 300°C) and it is only a match of time before test wells encounter hypothermal fluids in quantity (300 to 550°C). Extreme temperature environments will be found when attempts are made to exploit contemporary magma chambers (e.g., basalts in Hawaii) with temperatures in the 650-1200°C range in the zone of heat exchange.

Although only cased explosives might seem of interest, uncased explosives in intimate contact with borehole walls or pumped out into fractures and pore spaces may offer significant stimulation advantages [70].

Current explosive technology permits the construction of explosive-stimulation charges for temperatures up through 400° C; at higher temperatures such devices become extremely expensive. Whether a stimulation is by stress-wave effects, jet penetration, or bullet penetration, the energy source is presumed to be an explosive whose stability and performance are compatible with the conditions of intended utilization.

The possibility of post-shot toxicity or contamination must also be considered. Charges with high outputs of mercury or other poisons should be carefully controlled with respect to quality [69].

There are several projects within the framework of the Plowshare program which propose utilizing nuclear explosions for the recovery of natural gas and geothermal energy from dry geothermal anomalies. The Plowshare concept suggests the use of nuclear devices fired deep in natural hot rock to create a large cavity filled with fractured rock from

which the sensible heat* can be removed. The removal of heat would be accomplished through a closed-cycle flow of injected water or other coolants. This flow cycle (cavity - steam turbine - condenser - cavity) also will provide a slurry of various metal ores and chemicals, and a geothermal plant may develop into an unique base for the generation of electric power and the extraction of various marketable chemicals. Sites for such plants are possible wherever dry, hot geothermal anomalies are found. In this way, favorable geological formations can be selected in order to eliminate or substantially reduce the impurities in the natural steam system. In addition, this approach would greatly reduce the need to rely on the rare simultaneous occurrences of a number of geological factors necessary to produce geothermal steam of the required quality and quantity. From the practical point of view, geothermal energy represents only a very slight fraction of the internal heat of the Earth. The amount of the thermal heat of the Earth is at least 10^{33} cal and is more than ten times the caloric value of all exploitable fossil energy in the Earth and the nuclear energy of fissionable materials obtainable by mining. In fact, geothermal energy is essentially nuclear energy from a large natural nuclear reactor situated in the crust and mantle of the Earth [3]. Several optimistic experts, foresee future exploitation of the mantle, with highly advanced equipment, to tap geothermal energy almost anywhere on the Earth.

The possible couplingof Plowshare with geothermal power to produce electricity first appeared in a paper by Professor George Kennedy of UCLA at the Second Plowshare Symposium in 1959.

Battelle-Northwest carried out an additional analysis of the potential of Plowshare augmented geothermal power that appears extremely attractive.

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* Sensible heat is the heat involved in cooling a piece of any material like rock or water through a given temperature range. It is different, for example, from evaporation or fusion; it is the heat capacity itself that is removed.

If this approach in successful, many of the limitations which apply to the current geothermal plants will be removed. It would no longer be necessary to find steam and live with the resultant limitations. Hot rock is the key requirement and a reasonable amount of surface water is required for condenser cooling. These characteristics would make possible the production of high temperature (316-427°C) and high pressure (up to 3000 psi) steam.

The technical feasibility of the Plowshare created cavity has been demonstrated, and experience from several Plowshare devices and hundreds of underground weapons tests allow a reasonably accurate prediction of the cavity size and rubble produced. Perhaps the key problems in developing a Plowshare augmented geothermal plant will be adequate assurance of no unreasonable seismological disturbance and the obtaining of public acceptance. There are a number of other problems which must be solved before this concept is reduced to practice. These include: development of a device which is operable at high temperature, determination of the fracture volume from which heat can be extracted, design of a generating plant which will withstand the seismic shocks of these devices, and the determination of the radioisotope distribution in the system.

The preceeding comments are based on preliminary analysis of the concept. It is recognized that a more-in-depth feasibility study is required before firm conclusions can be drawn. Also, a demonstration experiment is required to prove the concept in practical application. The large potential that geothermal power has as another major energy source warrants an in-depth study [71].

The Plowshare concept for deep fracturing deals with <u>nuclear explosives</u>, which become more efficient in size and cost for yields above about 3 kt, and have proved useful for large-volume fracturing of underground formations. Special nuclear explosives are being designed for use in deep-emplacement wells of diameters nominally those employed by the oil and gas industry. Nuclear explosive stimulation of natural gas production in

deep, low-permeability gas fields is currently under study in the United States with the 29 kt. Gasbuggy experiment, the 40-kt Rulison experiment, and several other experiments now in the planning stages. In the Soviet Union, nuclear fracturing has been successfully demonstrated for the stimulation of oil production. The use of low-yield (5-100 kt) nuclear explosives also appears promising for the recovery of geothermal energy [59].

In March 1975, Los Alamos National Laboratory and Research and Development Associates - RDA of California proposed to the Energy Research and Development Administration - ERDA, a new version of Plowshare for developing geothermal sources from dry hot rocks utilizing H-bombs for creation of salt cavities in salt domes. Entitled "Pacer", the project seems to be the ultimate in "can do" thinking by its proponents. However, the proponents of the Pacer concept realize quite well that they cannot go very far with the plan unless they can convince the public to accept it, and obtain financial backing from the government. It has been estimated that extensive study and testing will require about 13 million dollars per year for the next 3 years. The economic feasibility of the project is quite sensitive to the cost of the thermonuclear devices, and the program's critics think that cost will be the plan's downfall, even if it proves technically feasible [123].

Fig. 8 is a schematic cross section of a hypothetical natural geothermal system and an explosion-stimulated geothermal aquifer. By appropriately controlling production rate and steam quality in the explosion-fractured wellbore, it may be possible to optimize the production of energy from the reservoir.

The generation of electricity from geothermal heat requires the production of about 1.7×10^4 lb/hr of saturated steam per megawatt of electricity. Tolerable amortization of a power plant and production system may require steam-production rates in excess of 1 million lb/hr for periods of 20 to 40 years. The energy content calculations given above indicate that to sustain steam production on such a massive scale, it may be necessary to

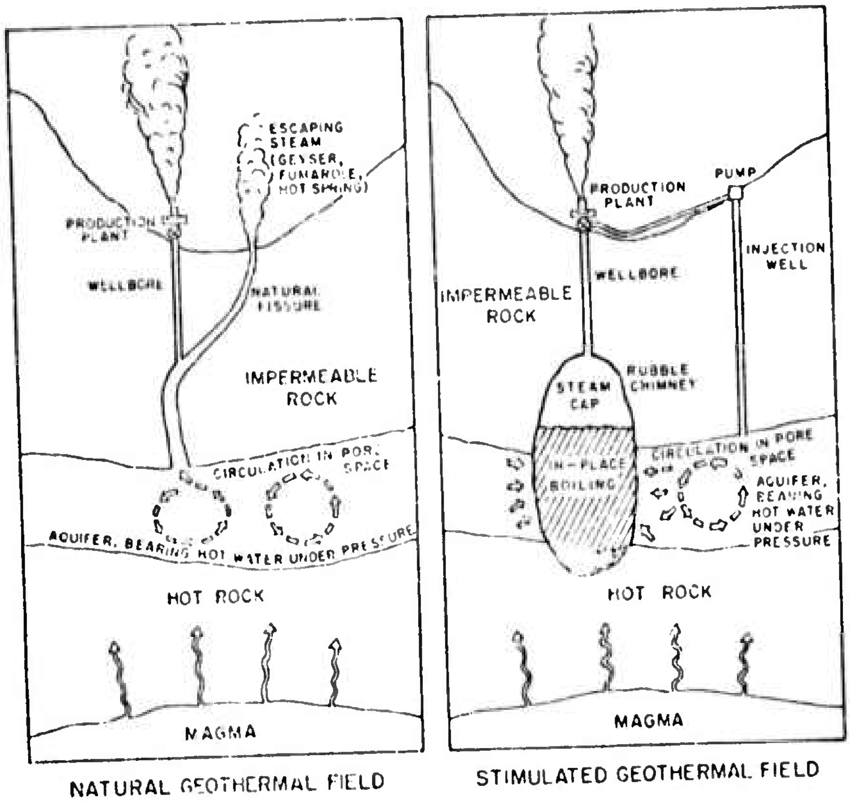


Fig. 8. Schematic comparison of a natural and an explosion - stimulated geothermal field [59].

recover energy from the hot, porous rock as well as from the thermal fluid in the aquifer. Thus, the economic feasibility of producing electric power from low grade geothermal resources appears to depend on engineering design that can deal with limited delivery per well, and limited volumetric energy content in the aquifer or limited reserves of the geothermal fluid.

Several methods of production can be considered with respect to these two goals. In one method the hot, compressed water is produced to the surface and flashed in steam in surface equipment and the cooler residual water is returned to the aquifer. In a second method, a gradual, controlled reduction of pressure, throughout the production period, causes a boiling front to recede into the fractured rubble chimney and eventually into the aquifer formation. In the third method, one of particular utility

where the geothermal waters are high in salinity or valuable mineral content, two rubble chimneys are operated cyclically; steam is flashed in one chimney until the residual brine reaches a maximum concentration, whereupon flashing is transferred to the second chimney, while the first is pumped free of its saturation brine chiefly to allow it to self-recharge but perhaps also to extract its mineral content [59].

The environmental effects of geothermal energy extraction stimulated by nuclear explosives include the potential release of radioactivity to the atmosphere and to ground water. For any underground nuclear explosion the possibility of seismic damage to natural formations and to man-made structures must be evaluated. The explosion seismic shock might also cause small natural aftershocks in the local vicinity or trigger natural volcanic eruptions and hydrothermal explosions [67].

Geochemical complications. Most natural minerals have significant solubility in hot water, and their solubilities increase with temperature and pressure. This fact may have both favorable and unfavorable consequences. If the reservoir does in fact grow downward and the temperature of the circulating water increases above the initial temperature of the rock in the initial reservoir, expansion would cause the thermal fractures to close again, if it were not for the solution and perhaps reprecipitation of minerals. The water rising to the surface will contain minerals that may be expected to corrode and plug the heat exchanger. However, some of these minerals may have commercial value, and their recovery from the water may be profitable. Certainly, an intensive study must be made, both in the laboratory and in the field, of the solubility and precipitation of minerals in solution under realistic conditions of temperature and pressure, if we are to understand and exploit the thermal cracking process [66].

In summary, the stimulation of geothermal fluid production from hydrothermal aquifers for producing steam to generate electricity appears to be technically feasible. Several potential methods of production are possible to optimize the recovery of the heat stored in the geothermal

aquifer. It is apparent that research is needed not only to study these methods, but also to develop a method for evaluating the changing potential resources across the fluid-production lifespan needed to depreciate capital investment.

The ability to evaluate the economic feasibility of explosion stimulation for development of geothermal resources and to determine optimum modes of production depends on the development of improved methods of geothermal reservoir engineering. Methods for the optimum removal of geothermal fluids must be based on a thorough knowledge of the recovery mechanisms operating within the reservoir, including fluid expansion, liquid vaporization, and the segregation of liquid and vapor (gravity drainage), as well as the influx of fluids from adjacent or underlying aquifers. The deposition and production of minerals must be considered, as well as the environmental effects due to the explosion and subsequent geothermal production. Thus a rigorous evaluation of geothermal -- aquifer stimulation requires study of a number of thermophysical, hydrodynamic, and chemical parameters [59].

3. <u>Drilling and testing technology, equipment, and instruments.</u>

Having selected a promising thermal area on the basis of surface manifestations, geology, hydrogeology, geochemistry and other methods, it is then necessary to undertake detailed surveys to determine the best location for exploratory drill sites. The number and depth of the exploratory holes will be determined by the results of these detailed surveys, the objective being to locate the center or the hottest part of the system and to determine the minimum depth to a permeable horizon or structure within the high temperature region.

It is not only the function of the geologist to select well sites, but also to assist the drilling engineer to program the wells. Together they must decide on the depth and diameter of the well, the casing program to be used, the frequency of collecting and the location of core samples, and the

frequency and types of test measurements. Well before the drilling program is started, a drilling engineer should join the exploration team in order to write the engineering specifications for the drilling equipment, casing and supplies and to ensure that well locations are properly prepared and that the necessary quantity of water for drilling is available at the well sites [4].

Exploratory drilling as contrasted to development drilling should aim for maximum data essential for evaluation. Results of Steamboat Springs, Nevada, indicate that cable-tool drilling provides the best bottomhole temperatures, obtained as drilling progresses. Diamond drilling provides the best geologic control, with satisfactory temperatures. Rotary drilling with large rigs is so expensive, holes progress so rapidly, and original ground temperatures are disturbed so much that few reliable data can be obtained. On the other hand where preliminary evaluation of a geothermal area is favorable, deep large-diameter holes may demand large rotary drills for production wells.

Deep drilling of hot water areas probably will not encounter any major increase in temperature until the base of circulation of meteoric water is approached, perhaps at depths as great as 10,000 feet. Much costly drilling can then be avoided [11].

Exploratory drilling may begin if required to assist the interpretation of the surface work - e.g., for additional geological or hydrological information, or to aid the interpretation of the geophysical data; but the holes should be located to assist this work rather than to test possible steam or hot water production. Core samples will be taken for petrological examination, especially for the rank and intensity of the hydrothermal alteration, and also for the measurement of physical properties, such as density, porosity, permeability, and magnetic polarisation. Temperature, pressure, and water level will be measured in the hole, and if it is capable of discharging steam or hot water, this will be metered as for production holes.

These exploratory holes may be of small depth and diameter, so long as they provide the information required, and they need not be elaborately equipped for full-scale production, which is not their purpose. In some cases, however, it may be possible to combine the two functions in the same hole. This then forms part of the proving program also and is drilled and equipped accordingly. On the other hand, the scientist will frequently desire information from below the optimum producing horizon, and some of the exploratory holes may therefore be drilled to much greater depth. This is particularly important in certain types of field where hot aquifers lie one above the other. Such deep holes provide useful information about the lower limits of a hot aquifer, and at later stages they may be used to give early warning of adverse changes at depth [16].

Much care is needed in making and interpreting testing instrument observations as geothermal measurements differ slightly in principle from those in other fields of engineering. Accuracy is dependent on the behavior of the fluid system, the sensitivity of the method, the quality of the equipment and instruments, and the standard of testing. Therefore, frequent calibration, repeat tests and checks of equipment and methods are vital to sustained satisfactory results.

Many downhole instruments have been developed for use in the petroleum industry to provide information about the reservoir, or to help in the drilling. While most of these are of value in geothermal drilling, understandably only some are suitable for steam service. High temperatures have limited the type and range of equipment which can be used, and have confused interpretation of the results.

Various geophysical logs, such as electrical resistivity, have been made in geothermal wells in order to correlate the formations, to indicate porosity, or to calibrate surface geohpysical surveys.

The following are some major instruments used during exploratory drilling, and in the production stage:

Bourdon types gages cover the whole range of pressure, from sub-atmospheric to values exceeding 50 bars (700 psi).

Aneroid barometer is used for measuring atmospheric pressure. An accurate means of measuring low pressure, or pressure differences (such as across a flow orifice) is with a glass manometer or U-tube, usually containing mercury but sometimes water or other light fluid for very small pressure differences. Pressure values may be indicated on circular dials, and/or recorded continuously on chart. The various pressure recorders may take disc or strip type charts, be spring or electrically driven, and operate over a wide range of speeds.

The instrument used commonly for downhole pressure measurement was developed initially for petroleum wells, and subsequently modified in the clockwork chart drive mechanism to withstand the high temperatures of geothermal wells. It is a vapor-filled helical Bourdon tube joined to a bellows unit, on the outside of which the well pressure acts. The Bourdon tube, thus sealed off from the well, scribes a line on a cylindrically wound chart driven axially at a constant rate.

Downhole pressures have also been measured by slowly forcing gas (e.g. nitrogen) down small diameter tubing, and reading the stable gas pressure at the surface. The tubing must be shifted for each depth to be measured, and again temperatures must be known in order to calculate the weight of the gas in the tubing (and to correct the tubing depth). This method is too cumbersome for general use.

With the advent of electric logging cables which will operate in the hot well conditions, pressure transducers with surface recording can be expected as instruments for the future. Simultaneous recording of downhole temperatures and pressures should be the objective.

The water level in a well is normally measured with a cylindrical float suspended on a wire line. Twin core cable can also be used to complete an electrical circuit when the water is reached. Some wells have

a mixed phase zone between the steam and water columns, which prevents the detection of a recognizable water surface.

Of the instruments which depend on the thermal expansion of a liquid, the mercury-in-glass thermometer has the widest use in geothermal work. It covers the full range of temperatures met, is stable and accurate, simple and cheap, and can be used in nearly all surface applications. Although other instruments give much superior results downhole, its maximum recording version can give limited but worthwhile information in subsurface work.

Liquid expansion instruments also include those in which pressure changes cause movement of a Bourdon tube, as in pressure gauges.

Bi-metallic instruments are commercially available for surface applications, and their principle has also been applied in the geothermography, (developed specially for use in geothermal wells), in which the swing of a bi-metallic reed is scratched across a plate whose longitudinal movement is controlled by jerking the wire line at each depth.

The geothermograph may be run, read and calibrated with the same surface equipment as used for the downhole Bourdon-type pressure (and temperature) gage. The highest temperatures recorded in geothermal wells, just over 300°C, have been measured with this instrument. Its accuracy is not better than 2% of the range.

Thermocouples have been used both for surface and of downhole measurements. The greatest difficulty in downhole use is in finding a thermocouple cable which will retain its insulation for an economic number of runs. Surface indication is given of downhole conditions, either by measuring the direct deflection on a millivoltmeter, or more accurately by the null method, in which an electrical balance is measured with a potentiometer. Either direct indicating, or automatic recording, may be used in these measurements (American National Standard, 1964).

Thermistors are temperature dependent resistors having a negative temperature coefficient, in the range of about 4-5 x 10^{-2} °C, and are used for geothermal prospecting in shallow holes. They are based on a metal oxides compound processed by metal ceramics technology. Using the ratio of the temperature resistivity coefficient of the thermistor to that of the comparing resistors in the range evaluated, it is possible to determine the fundamental error due to the ambient temperature influence. The error is approximately 0.01 - 0.02°C within the measuring range 0-50°C and ambient temperature range 15 $\pm$ 20°C. The thermistor thermometer is the most convenient solution as far as geothermal prospecting conditions are concerned. The disadvantages of the thermistor transducers are its relatively bad long term stability and its nonlinear resistivity temperature function. In general, the instrument properties assure the sufficient accuracy reserve for further research and study of the temperature field [105].

Resistance thermometers. These sensors take advantage of electrical resistance changes which accompany temperature variation. Dependable materials include:

- platinum wire, which has a positive increase in resistance with temperature rise;

- metal oxide beads, with a larger, negative characteristic.

These latter are called thermistors. The references show a number of circuit systems which may be used, as well as an array of measuring instrument hoop-ups possible, as for thermocouple practice. A 3-wire cable and a null balance circuit is suitable for downhole work.

Both thermocouples and resistance thermometers can be instrumented to provide a direct digital output suitable for electronic data storage or computation. Resistance thermometers are considered more accurate, and for downhole work operate with normal conductor cable. Both of these thermometer types approach the ideal of continuous recording with

little lag, in contrast to the set-wise operation necessary with the geothermograph and the vapor pressure thermometer.

Calorimeters measure the volume and heat produced during a convenient time interval. Essentially, the calorimeter is a tank partly filled with cool water into which the flow is passed for a measured period. From the gains in volume and temperature of the water can be calculated the heat and flow rates. While, in theory, all flows may be measured by such a sampling calorimeter, superheated steam and hot water are usually best measured in othe ways, and calorimetry is confined largely to mixed flows. The tanks, however, may be used also for volumetric measurement such as the calibration of hot water weirs and flumes [74].

Many methods have been suggested for measuring the quantities of steam and water issuing from geothermal boreholes. Four methods that have been used in New Zealand are described below:

Beta Ray Method, where a beta ray source is mounted on one side of a nozzle and a Geiger tube probe diametrically opposite.

Gas method, where samples of two phase mixtures are taken either side of a throttling valve and the gas content of the steam phase is analyzed in each sample and the enthalpy calculated. A small cyclone is attached at each point and a sample of steam/water is extracted and then separated.

Magnesium sulphate injection method, where a known concentration is injected at a steady rate into two-phase mixture and sampled after adequate mixing, and the magnesium content of the water phase analyzed and the flow calculated.

Critical lip pressure method, where the pressure is measured at a predetermined point near the discharge of a borehole under pressure to the atmosphere. An empirical relationship has been found of mass flow, enthalpy, and critical lip pressure [77].

Venturi flow meter (Fig. 9), developed for cold water use, is suitable for measuring the low flow and discharge of geothermal hot water in the open.

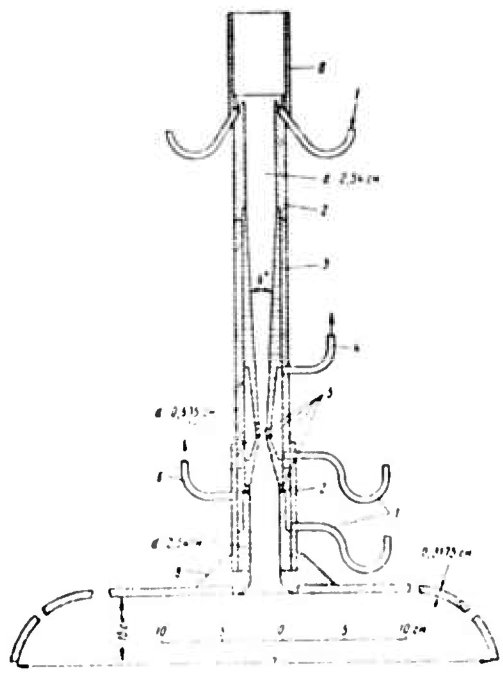


Fig. 9. Venturi flow meter [76].
1- condensation trap copper tube (Ø 1/4"); 2- sleeve; 3- cast fiber grass; 4- copper tube (Ø 1/4") for low pressure manometer; 5- outlets (Ø 1.5 mm); 6- copper tube (Ø 1/4") for high pressure manometer; 7- fiber glass cone (Ø 61 cm); 8- asbestos.

In general, steam jet velocity is measured by vane-type or cup-shaped anemometers, similar to those used in meteorology. However, the most reliable instrument is the aerodynamic Pitot tube (Fig. 10) by which steam jet velocity is obtained from absolute flow pressure, static pressure, and steam density (depending on its temperature and environmental pressure).

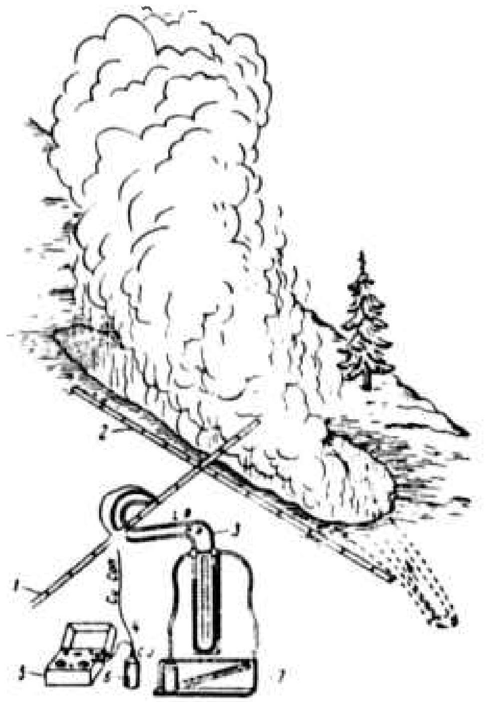


Fig. 10. Measuring of discharge of a fumarole by aerodynamic Pitot tube [76].

1- Pitot probe; 2- surveying rod for profile marking; 3- polyethylene tube; 4- thermocouple cable (copper constantan); 5- potentiometer; 6- thermos bottle with melting ice; 7- inclined manometer.

There are several types of separators designed for separating steam mixture into the steam and water and provide measurements under uniform media. Based on operation principles, there are volumetric separators, in which the steam is subjected to free evaporation, or centrifugal separators. The most common in the centrifugal separator (Fig. 11) where the steam mixture, running from the borehole at high velocity through pipes, is conveyed into the vertical tube-cyclone and through spiral installation and is subject to circular motion. Centrifugal force spatters the wat r against

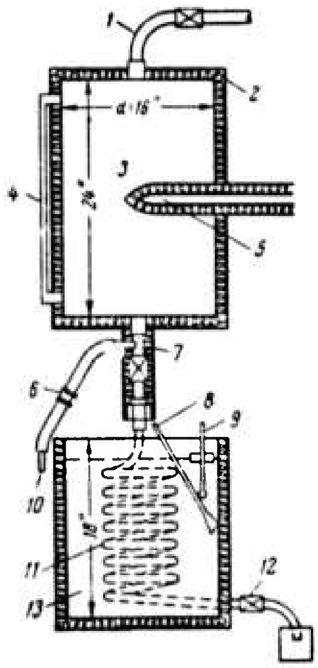


Fig. 11. Centrifugal separator [76].

1- steam pipe and inflow controlling faucet (Ø 1"); 2- compact insulation (separator, calorimeter and pipes); 3- separator; 4- sight glass; 5- inlet pipe (Ø 1") into separator; 6- pipe lock for water control; 7- pipe (Ø 1") and faucet; 8- mixing blade; 9- swimming thermometer; 10- water outlet; 11- copper-pipe (Ø 3/4") coil; 12- condensate discharge faucet (Ø 3/4"); 13- calorimeter (container with water, used for measuring enthalpy).

the wall of the cyclone, and the steam which is the much lighter component is collected in the central part of the cyclone. The inflow pipe is equipped with various measuring instruments, such as flowmeters, manometers, and thermometers. There are special outlets for withdrawing of water and steam for chemical analyses [76].

The above mentioned equipment and instrument are only a few of several used during exploratory drilling. Therefore, various calorimeters, thermometers, flowmeters, manometers, etc. of different standards used in chemical, geological, and hydrogeological analyses are not described, as they are beyond the scope of this study.

The depth of exploratory wells, as their location, must be determined on the basis of the preceeding surface surveys. The target depth may be established on the basis of geologic sections or from the recognition of significant horizons found from resistivity or seismic profiles. As geothermal reservoirs are often structurally complex, predictions of the depth to possible production zones can be highly inaccurate. It is therefore desirable to have drilling capacity available to reach depths of about 1,500 m, even though it may eventually prove necessary to drill to only 1,000 m or less.

Adequate logging and testing of exploration wells is essential. The testing equipment should be at the site before drilling begins, because the manner in which the well should be completed can best be determined by the information provided by these tests.

Electric logging of geothermal wells is expensive, and therefore rarely done. The high cost is due to the fact that geothermal wells are usually drilled in regions where oil field logging services are not easily available and because electric logging of high temperature wells requires specialised equipment. The geologist, therefore, must make correlations and identify production intervals on the basis of lithologic, drilling time, and temperature logs, and probably most important, the occurrence of lost circulation intervals.

As in all drilling, a lithologic log must be made from the drill cuttings, and rock type identifications should be checked at reasonable intervals by taking cores. The identification of lithologic boundaries can be facilitated in many cases by correlating the lithologic log with the drilling time log. In

addition, every attempt should be made to correlate the lithologic log of the well with the stratigraphic section obtained from surface geologic mapping. Hydrothermal alteration of the material obtained from the well, however, often makes correlation very difficult, if not impossible.

Spot downhole temperatures taken with maximum recording thermometers are not entirely adequate and should not replace temperature logs obtained with continuous recording instruments such as the Amerada type gauge. These gauges are not expensive, and do not require a field service team to operate, as do the electrical logging methods. Temperature logs should be run during drilling as often as prudent drilling practice allows, and daily for a period of several weeks after drilling is completed and before the well is allowed to flow. Retrograde temperature zones identified during drilling should not be cased off until it has been determined whether these are actually cold zones or whether they are hot zones which, because of good permeability, have accepted a large quantity of cool drilling fluid. Correlation of the temperature log with zones of lost circulation will help to resolve this question.

Permeable zones known to control thermal fluid should be tested quantitatively as they are encountered by running water injection tests at various flow rates and, at the same time, measuring down-hole pressure build-up with an Amerada gauge. This test will give an injectivity index which is a measure of formation permeability. Because geothermal wells tend to clean thermselves during the first few days of production, injectivity indices are usually considerably lower than the comparable productivity index. Nevertheless, injectivity indices provide a means of quantitatively comparing one permeable zone with another in the same well. The same information can be obtained after the well is brought into production only by expensive and time-consuming tests involving the use of packers; or not at all, if the permeable zones have been cased off.

Production tests, which must be designed and supervised by a reservoir engineer, should be run as soon as the well is permitted to flow,

because the results of a quantitative flow test are essential for deciding either to continue drilling additional wells or to abandon the area.

The decision to continue drilling additional exploration wells is an easy one if the first well has good production characteristics; if it is marginal, however, the decision may be extremely difficult. In such a case, a rational decision can be made only if it is known why the well is marginal. The three common reasons why a well either fails to produce, or produces only at a small flow rate, are low temperature, low permeability or a poor well completion.

If temperature is the problem and the chemistry of the thermal fluid from the well gives no indication of higher temperatures in the reservoir, serious consideration should be given to abandoning the area unless some subsurface information, hitherto unavailable, suggests that the well was not sited near the center of the thermal system.

If downhole temperatures are found favorable, but the well fails to produce because of lack of permeability, several more holes should be drilled to search for a permeable production zone; and if one is found, to confirm its geometry and orientation. The majority of geothermal fields depend on fracture, rather than intergranular, permeability for production, and fracture permeability is notoriously erratic. This is another reason why initial exploration wells should be programed as deep as available finances will allow. The deeper the well, the greater the chances of intersecting randomly distributed fracture zones.

If the problem is one of well completion, either the well should be reconditioned if possible, or another well should be drilled. Two common errors made in completing geothermal wells are "mudding off" of the potential production zones, and casing off of upper production zones in an attempt to find better zones at depth.

In hot water fields, a fourth reason why wells may fail to produce is that the reservoir rest level is too deep easily to allow unloading, and consequent flashing, of the high temperature water. If the reservoir is large and the temperature of the field is high, it may even be technically and economically possible in such a situation to pump the fluid to the surface.

The exploration phase of the project does not end with proving the existence of a high temperature geothermal reservoir having sufficient permeability for production. The next, and probably the most difficult, question to answer is what is the capacity of the field. Unfortunately, the structural complexity and the importance of fracture permeability in most geothermal fields make capacity projections, based on only a few exploration wells, highly unreliable. For this reason, there is not a sharp division in geothermal projects, as in the oil industry, between exploration and development drilling. The problem of predicting production capacities of geothermal fields is circumvented by having sufficient exploration capital available to prove at the wellhead a sufficient amount of steam to operate a minimum size utilisation plant economically. For a power plant, this size could be in the range of 20 to 50 MW. Assuming an average production of 5 MW per well, there should be sufficient capital available, after a discovery is made, to drill five to ten additional offset wells. Experience has shown if 'production' rather than 'information' is the immediate goal, then these offset wells should be conservatively sited; that is, the offset should not be drilled more than 200 to 300 m from the discovery well [4].

The development of new, less expensive techniques for drilling to depths in excess of 8 km would benefit geothermal, oil, and gas exploration greatly, though drilling research is needed at shallower depths as well. The major difficulties with present technology are in its application at high temperatures. Problems are encountered with rubber seals, valves, cements, drilling muds, heat shields, sound mufflers, etc. Formation testing in uncased holes can be useful in the exploration for reservoirs. Problems of isolating tested intervals in unconsolidated sands and in fractured reservoirs have not been solved. Inexpensive core recovery with reservoir fluid in place would be

useful in defining a model of a geothermal cell. Instrumentation for logging devices operating at temperatures above 180°C is urgently needed, as i. research on methods of transmission of information from the borehole face to the surface. Development of cheap, low-density, low-viscosity, thermally nonsensitive, thermally conductive, and high-surface-tension drilling fluids would lower drilling costs and leave the borehole face in a more nearly undisturbed state. Drill cuttings, cores, and logs should be preserved. The rotary drill must be improved and new techniques such as erosion drills, electric-melting drills, and turbine drills should be explored.

In addition to the more applied research, basic research should be pursued on physical properties of geothermal water-steam mixtures, thermal geophysics and hydrology, and computer modeling [6].

In general, the drilling equipment and instruments for the exploitation of endogenous fluids are very much the same as used in the oil industry. Experience gained by the oil industry has been applied to geothermal drilling with minor changes in the methods, machinery, and instruments.

The standard rotary rigs are used for wet geothermal drilling, and as a rule they are for medium-depth penetration, since steam producing wells are usually less deep than those producing oil (Fig. 12). Therefore, this particular use calls for some specific adjustments and minor modifications [60].

The time required for drilling is greatly influenced by the topography at the site, the ease of access, the hardness of the formation, the efficiency of the rig, the amount of casing required, the lengths to be cored and the number of meters to be drilled in the productive zone where mud losses are high. Under favorable conditions the following times are

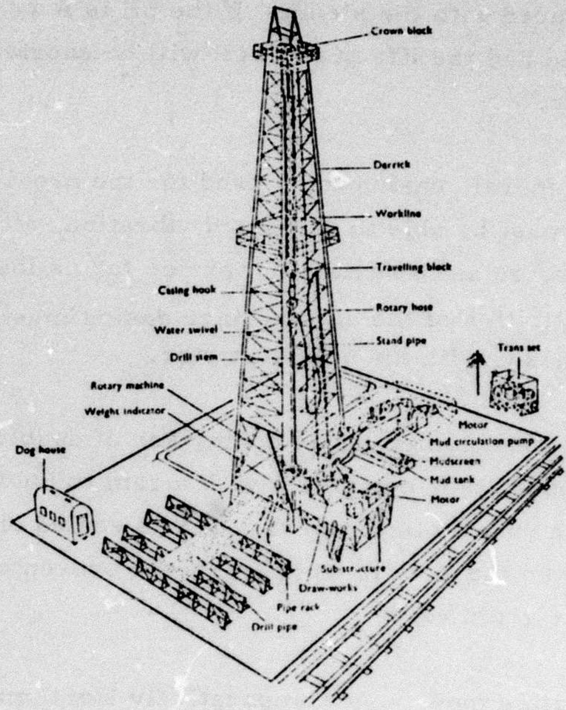


Fig. 12. Rotary drilling rig [73].

reasonable estimated:

Depth	Actual drilling	Finishing and testing
500 m	15 to 30 days	10 days
1,000 m	25 to 45 days	10 days
1,500 m	35 to 55 days	10 days
2,000 m	50 to 70 days	10 days

<u>Casing</u>. An important item in the planning of a steam production well is a proper casing program. A large volume of steam production should be expected from a large diameter well. But if a well is too large for the capacity of the steam formation it will not always produce abundant steam and is more likely to be incapable of maintaining a sustained flow. Also, if casing has not been put down to the correct depths, and hot

water occurs in higher formations, it may prove impossible to obtain a continuous flow of steam from the lower formation because of the incursion of hot water from above. Further problems arise from the pH values of the hot water produced with the steam. If the pH is low, the casing will be heavily corroded and the life of the well will be shortened and may even become uneconomic.

In general, casing to be used for the production of large volumes of steam must be able to withstand vibration, attrition through friction, wear and corrosion, so as to remain in service for as long as possible. To minimize the attrition of the slotted liner casing must be as large as possible by comparison with the hole diameter.

Wellhead equipment is comprised of double gate blow-out preventers, the upper stage equipment with a ram to hold the drill-pipe and the lower stage with a blind ram that can be sealed off without affecting the drill-pipe. When the hole is completed, the preventers are removed and replaced by the main valve.

Drilling mud. - At comparatively low temperature, around 150°C, drilling of geothermal wells is usually carried out with bentonite or other clay-based muds [73].

Drilling mud is mixed as required at each drilling site and is treated to give it properties designed to: carry drill cuttings to the surface, build on impermeable strong cake about the drill hole wall, control subsurface pressures by mud column density, and cool and lubricate the drill bit and surrounding formations.

Mud making and treating materials are as follows:

- bentonite and water for base mud,
- carboxy-methyl cellulose for water loss control,
- tannin for viscosity and gel strength reduction,

- caustic soda for alkalinity control,
- barite for density control, and
- diesel oil (normally 10 percent by volume of mud) for water loss control and increased lubrication.

It is expected that the newly developed high temperature muds of the lignite sodium surfactant type will greatly improve the drilling conditions [93].

Air drilling is rotary with circulating air instead of mud. This method has been tested over several years in various countries, and particularly good results have been achieved at the Geysers, California.

Particular features of this method of drilling are:

- high drilling speeds and low drilling costs (speeds 3 to 4 times greater, bit life 2 to 4 times longer than with mud drilling), and

- no damage to the production zone from circulating mud injected during drilling.

Air drilling has certain disadvantages and is unsuitable for formations bearing excessive water or with a strong tendency to slough. Mud drilling must then be used. It is usual practice to first drill the formation with mud and then resort to air drilling, or to drill with air in the production zone once the production casing has been put down and cemented in.

The air drilling rig is basically the same as for ordinary rotary drilling with mud circulation. It is adapted for air/mud circulation. The main parts of the rig are shown in Fig. 13 [73].

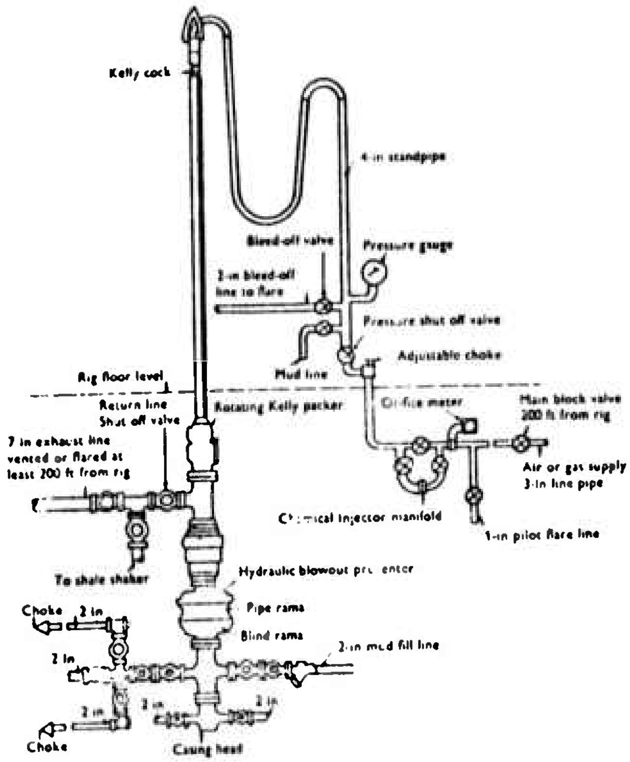


Fig. 13. Diagram of air drilling hook-up [73].

To exploit deep dry geothermal resources, Soviet scientists have suggested a long-range project to drill wells to a depth of 10 kilometers and create large subterranean "boilers" which would supply a steam-hot water mixture for a geothermal electric station of more than 1 million kilowatts capacity.

The designers of the Uralmash Plant (Ural Heavy Machinery Plant), Sverdlovsk, RSFSR, have developed plans for a drilling installation called "Uralmash 15, 000, " which will be capable of drilling to a depth of 15, 000 meters. The entire complex of the "Uralmash-15, 000" consists of a power plant, an engine room, and a pumping station. This installation will have a derrick over 60 meters high, with elevators for cargo and operators. The superdeep drillholes may be bored either by turbine or rotary methods [83]. It will be a complex of assemblies with its own electric power station and a number of engines. The power of the main generator will be approximately

10,000 kw. Four special pump (each 8,720 hp) will feed a special solution as drill mud into the well and flash out the rubbles. Provision has been made for an automatic control system with the use of television, and electronic computers for routine processing of data and control of drilling operations.

The following are available technical data on this installation:

Drilling depth	15,000 m
Hoisting motor capacity	3,130 hp
Drilling pump motor capacity	8,720 hp
Shaft diameter	760 mm
Shaft lifting capacity (maximum)	400 tons
Swivel lifting capacity (maximum)	450 tons

A specially designed mechanism will change a worn out bit without lifting the drilling shaft, hence eliminating creation of hydrodynamic impulse, and breaking of the drillhole walls [26].

In the vicinity of the small town of Saatly, Azerbaydzhan SSR, specialist are nearing completion of preliminary work associated with the drilling of a borehole with "Uralmash 15000" to a depth of 15,000 m. It is proposed that the entire work be carried out in two stages: first to a depth of [illegible],000 m., and then to 15,000 meters [75].

The Soviets are experimenting with unconventional tools to modernize the drilling of exploratory boreholes, construction of water wells in deserts, and laying underground communication and pipe lines.

Engineer M. I. Tsiferov*, an export in explosives and, since 1948, a pioneer in underground drilling with unconventional equipmer ,

* Major General, Technical Engineering Service (ITS), Soviet Army.

has designed and developed a self-powered underground rocket (Fig. 14).

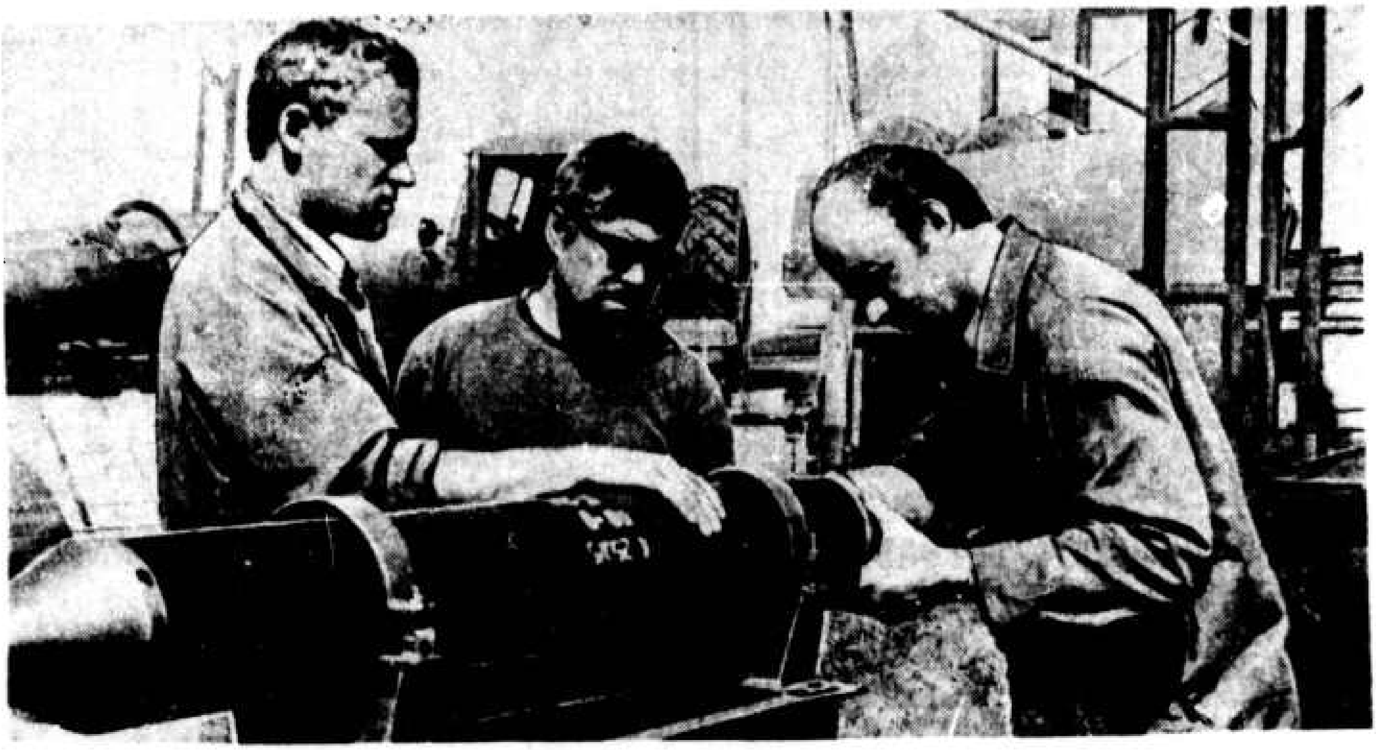


Fig. 14. View of the rocket during recharging [88].

The unique rocket head releases a gas stream which rotates the rocket and simultaneously disintegrates the soil encountered. The flame vortex drives the rocket forward and ejects the disintegrated materials. The rocket attains a penetration speed of 1 m/sec, creating an opening about one meter in diameter at the surface.

This rocket, registered under Soviet Patent No. 79119, is described as a device for drilling by the intense crushing of rocks with a gas steam (at a pressure between 500 and 2500 atm) produced by a generator built into the device. In addition, the device is designed to use small charges of high explosives instead of the gas stream. The average speed of the rocket exceeds the present speed of a conventional drill by about 100 times, with a potential drilling depth range of 20-25 kilometers without concern for the destruction of the rocket by the very high temperature encountered at such depths.

The underground rocket has an equivalent blasting energy of about 10,000 to 50,000 horsepower, with a potential of 10,000 horsepower or more. Operating in sequence, a number of these rockets could be used to reach the depth of dry geothermy and other natural resources. In this regard, the rocket has been field tested in an attempt to drill an irrigation well for a Saratov Oblast collective farm. Within 18 seconds, the rocket drilled a well 1 meter in diameter and 17 meters deep. The rocket is described as being only 1.5 m long, capable of carrying up to 200 kg of fuel, and fitted with a heat-resistant nosecone. The refueling operation takes about 20 minutes, and it is mentioned that a single fueling charge provides the capability for drilling about 10 boreholes of the type described above at negligible cost.

Basically, the drilling is accomplished by highly focused gas jets firing through several sets of nozzles in the head of the rocket. The tip (cutting) nozzles produce gas jets with temperatures of 1000-1500°C and a velocity of about 2000 meters per second, concentrating an enormous amounts of energy on a small area resulting in pulverization of the encountered ground.

Another set of back-angled nozzles firing almost tangentially from the base of the nosecone impart forward and rotary motion to the rocket. These side nozzles are used to widen the hole and, combining with the partially expended cutting gas, they also eject loose soil from the well at a rate of two tons per second.

Presently, Tsiferov is working on a new rocket with an automatic combustion-chamber cooling and fuel-feed system.

The rocket has been a main discussion topic at many meetings of the USSR Academy of Sciences, and has been considered as the best prospective tool for deep drilling. According to N. A. Chinakal, Corresponding Member of the USSR Academy of Sciences, the speed of this rocket enables a drilling capacity of over 10 kilometers per month.

At present, no additional data are available regarding the material used for the construction of the rocket, the type of explosives (liquid, solid or atomic), dimensions and graphical descriptions of the rocket, or the retrieval of the rocket for refueling or in case of technical defect [88].

In general, during the last decade, no great changes have become apparent in the design of drilling equipment. However, the Soviets designed their own separator with rather marginal improvement over those used by other countries, and the blowout preventer (on the base of wellhead connection) has been slightly modified to withstand the higher pressure [61]. The Soviets did not experience any blowouts during exploratory drillings, although they anticipated the possibilities in 1958 during drilling of the first rotary borehole in the Pauzhetka region [62].

Regarding the powerplants and prime movers for drilling rigs, diesel engines and the direct-current electrical motors have been considered. The diesel engine is used primarily in the strictly exploratory phase, when electric power distrubution points are at a considerable distance from drilling site. The electrical motor may prove highly economical in the subsequent stage, when a power generating plant is already in operation and may easily supply the drilling site [60].

Besides many problems in geothermal exploration, the blowouts represent a major obstacle during drilling operations, and in some cases after a long time of exploitation of a producing well.

Common factors in the blowouts which have occurred while drilling have been the following:

- wells were drilled in areas where little was known about the formation of sites,

- the circulation return of drilling fluid was lost, and the well came under pressure or remained under pressure for too long,

- insufficient casing in the well, and

- there was a ready path for the steam to reach the surface outside the drill hole.

Present practice in preventing blowouts is to inject grout in stages to a depth of 100 ft adjacent to the bore, tapering to a depth of 50 ft approximately 30 feet away from the bore. Initially, the grout holes are drilled at 10 - foot centers in both directions. Should any hole take a large amount of grout, intermediate holes are drilled and grouted. A typical consolidation grouting job would take about 100 tons of cement, although on one occasion 1,650 tons were used.

Consolidation grouting will not prevent a blowout, but if one occurs, it will be deflected away from the well for a length of time which will allow all the drilling equipment to be removed.

Care must be taken when a well is being drilled and when it is in service to ensure that the casing is never subjected to thermal shock, either by cooling or heating. However, during the life of the well there may be occasions when it is essential that the well be quenched. Quenching by pumping water into the wellhead should be avoided except in an emergency. The most satisfactory procedure is to pump water through drillpipe or tubing which has been run below the casing shoe. The pumping rate should be slow initially but can be built up to a maximum, which will depend on the well being quenched. At Wairakei, New Zealand, it varied from 100 to 300 gallons/minute.

To control wellhead pressure during drilling, the well should, so far as practicable, be prevented from coming under pressure which should be removed as quickly as possible. In addition to the danger from blowouts, other circumstances make it inadvisable to carry on drilling while the well is under pressure. In the majority of cases, the well comes under pressure because of inflow of formation fluids following a loss in circulation. The rise

can occur relatively quickly and in order to prevent the well from discharging, thus endangering men and equipment, blowout preventer equipment is provided on the wellhead. The blowout preventer is essentially a steel housing containing a cylindrical rubber packing unit designed that it will close on any part of the drill string or tools in the hole, and is hydraulically operated. On the smaller rig, the preventer is pumped up by hand, but on the larger rig, the bag is automatically inflated, thus the preventer can be shut off almost instantaneously.

However, the most effective way of taking the well off pressure is to inject water through the drill pipe or tubing as close as possible to the loss of circulation or the point of entry of the hot fluid. Blowouts from wells which have been in service for some time are generally due to an escape of hot fluids into the upper formation through broken casing. The only satisfactory method to control a blowout is to drill a controlled directional hole to intersect the feed to the well responsible for the blowout [89].

However, when the output of a well does not warrant an economic exploitation, the geological and thermal data may suggest probing deeper. In this case, particular operational techniques are necessary to ascertain the possible productivity of deeper layers. Although the sudden release of a huge mass of steam and water can be very impressive, the blowout of a steam well presents no great danger and causes little damage to equipment. As a rule, moreover, the blowout is controlled, except in cases when the hydrostatic head inside the well drops suddenly and falls below the pressure of the steam inside the layer.

In general, there are two types of controlled blowout:

- once the producing fracture is reached (during drilling of the pervious layer), and once mud circulation is lost, the hydrostatic level inside the well stabilizes, thus creating equilibrium between the weight of the head of water between the water surface and the fracture. As long as water is sent into the well (at its external ambient temperature), the rock constituting the

well walls is cooled. Maximum cooling occurs at pervious levels having the greatest absorption characteristics. Under these conditions there is actually no steam production, or at least none sufficient enough to originate a blowout. If the well is to start production it is left idle, that is, the introduction of water is stopped. During this phase, the gaseous content of the endogenous fluid is released in the form of bubbles which emulsify the liquid column, while the temperature generated by the heat source tends to rise again, and the cooling process is finished. The temperature in the well is raised by conduction of heat from the rock and by intake at the previous levels. As a consequence the column of heated and emulsified water is expelled violently from the well, starting the blowout phase, which then continues with strong jets of steam and hot water, and the ejection of rock fragments.

When the action of gas and temperature is not sufficient to originate blowout due to the lower gas content of the steam or higher pressure of the hydrostatic head, blowout can be stimulated by decreasing the weight of the liquid column, for example by means of a plunger piston operation. This technique consists of continuous extraction of water from the well.

However, there are various methods of opening up steam wells, such as swabbing, introducing liquid nitrogen, compressed air, foaming agents, and decompression. Because they are beyond the scope of this study, these methods will not be discussed in detail [104].

4. Transmission of geothermal fluids

In a typical geothermal field there will be a number of wells connected to one or more pipelines leading to the plant which may be located a considerable distance away. The fluid transmitted may be steam, hot water, or a steam-hot water mixture if separation is effected at the plant instead of at the wellheads. Some fields can be best exploited by operating groups of wells at different pressures with a separate transmission system for each group.

The wellhead pressure in a closed well may be very high and much in excess of that occurring under operating conditions when the flow is controlled. This is particularly so in wells which produce steam-water mixtures with which gas is associated. When standing shut, the gas may accumulate at the top of the well and depress the water column until pressure equilibrium is established. The pressure can be relieved by a continual small discharge to waste through a bleed valve installed below the wellhead master valve.

Wells producing only steam can be directly connected to the steam transmission system, but where steam and water must be separated at the wellheads, various arrangements are possible depending on whether the separated water is to be wasted or piped away for further use.

<u>Steam transmission</u> systems will normally consist of one or more large diameter main pipelines with smaller branch pipes from the wellheads connecting into them at convenient points. The distance of transmission may be some thousands of feet and in a large development several pipelines may be required stretching into different parts of the field. In the system's design one of the main considerations is the choice of pipe diameter so that the drop in pressure between wellheads and the delivery end of the pipeline is not excessive. The choice of operating pressure will depend on the discharge characteristics of the group of wells and their productivity at various wellhead pressures. Pressure drop, which is mainly due to frictional resistance to flow, causes the energy in the steam to be degraded and, if excessive, imposes an undesirable pressure increase at the wellhead and a consequent reduction of output. Also, contributing to the pressure drop are the losses due to disturbance of steady flow created by valves, bends and other fittings, as well as by sudden enlargements or contractions of diameter.

Pressure drop is also proportional to the density of the steam. Consequently, for the same pressure drop, low pressure steam can flow at higher velocity than steam at a higher pressure in an equivalent pipe. However, the velocity should not be so high as to cause erosion of valve seats and other exposed parts.

Lagging of pipes and vessels with an insulating material will minimize heat losses, but some condensation will normally occur unless the steam is sufficiently superheated. With separated steam it cannot be guaranteed that some salt-laden water will not be carried over from the wellhead separators. Therefore, repeated dilution of this water with condensate and partial removal serves to purify it in transit. Any small quantity of water which may be entrained in the steam reaching a turbine would then contain only a negligible quantity of sodium chloride which, if in greater concentration, could give rise to stress corrosion cracking of turbine blades.

Hot water transmission. When hot water at or near boiling point is to be transmitted through a pipeline, precautions are necessary to ensure that the pressure at all points in the pipe is higher than that corresponding to the boiling point so that formation of steam is suppressed. If the pressure was lower, steam would form as bubbles or pockets in the water, and if a pressure rise should occur collapse of the steam could cause serious water hammer and possible rupture of the pipe. Hot water at moderately high pressure and temperature should be regarded as much more explosive, than an equal volume of steam at the same temperature and pressure in an equivalent pipe or vessel; at 200°C, for instance, it is about 12 times more explosive. To maintain an adequate margin of pressure to suppress boiling, pumping can be used to increase the pressure, or the temperature can be decreased to below the boiling point by introducing cooler water. A combination of both methods may be possible.

Due to friction there is a gradual decline in pressure during flow along a pipe and a further decline due to loss of hydrostatic pressure if it is on a rising gradient. If the gradient is falling, the hydrostatic pressure increases and may more or less counterbalance the frictional pressure loss.

An example of hot water transmission is provided by a pilot plant installed at Wairakei in New Zealand. The scheme was designed for five high pressure wells and two intermediate pressure wells operating at approximately 200 lb/in^2 and 70 lb/in^2 respectively. The length of the

pipeline was about 5,000 ft and it delivered the hot water to a flash plant located alongside the power station. Flash steam was produced in two stages at pressure of 50 lb/in^2 and just above atmospheric pressure. This scheme is illustrated in Fig. 15 which shows only one of each class of wells connected to the hot water main.

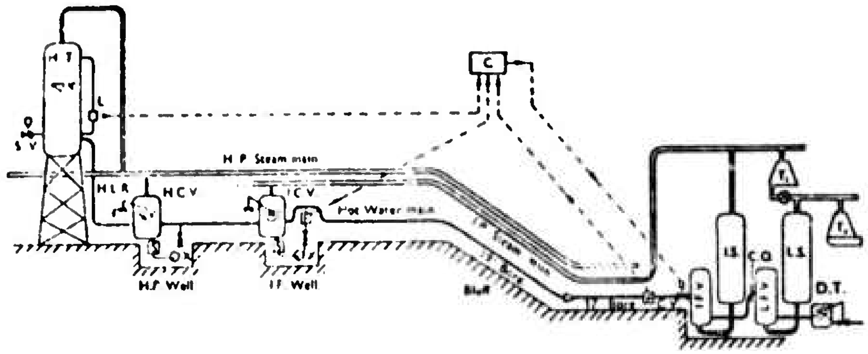


Fig. 15. Hot water transmission system [79].

Key

H.C.V.	H.P. collection vessel	C.V.	Motor operated control valve
I.C.V.	I.P. collection vessel	I.F.V.	I.P. flash vessel
H.T.	Head tank	L.F.V.	Low pressure flash vessel
S.V.	Motor operated spill valve	I.S.	I.P. Scrubber
L.	Level detector	L.S.	L.P. Scrubber
F.	Flowmeter	D.T.	Drain tank
H.L.R.	High level relief	T_1	I.P. turbine
S.	Strainer	T_2	L.P. turbine
X.	Extraction pump	C.O.	Control orifice
C.	Computer	H.P.	High pressure
- -	Steam connections	I.P.	Intermediate pressure
——	Hot water connections	L.P.	Low pressure
· · ·	Electrical connections		

Vapor pumping is another method of pressurizing which has been suggested. Fig. 16 diagramatically shows its application where two separate steam pressure systems are available, but could be operated less efficiently by using the atmosphere as the lower pressure system. As for the scheme described above a similar hot water collection vessel "A" is provided for each well and a common heat tank "H" for the whole group of wells. In addition a lift cylinder "L" is associated with each collection vessel. Valves V_1 and V_2 are controlled by signals when the water in vesssel "A" reaches its maximum and minimum levels. N_1 and N_2 are non-return valves.

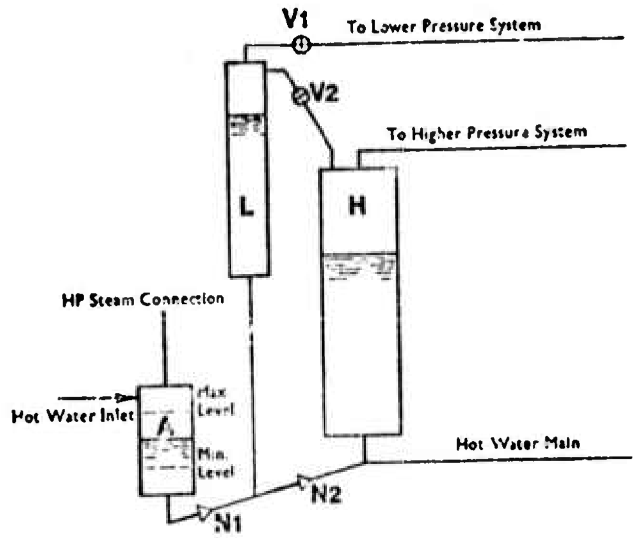


Fig. 16. Vapor pumping [79].

In using two-phase transmission for a scheme intended to utilize the hot water, some advantages may be gained by transmitting in to one or more pipelines the mixture of steam and water as produced from the well with separation taking place at the point of utilization. Much of the equipment at wellhead would then be eliminated including separators, hot water pumps, water collection tanks, and all the associated pipework. Because there would be no need to suppress boiling in the pipeline, a head tank on the hot water line would also no longer be required.

After primary separation the hot water would be rejected or would undergo a reduction in pressure in a flash plant to produce steam in one or more stages at lower pressure with final rejection of residual hot water.

The character of flow in a pipeline of steam/water mixture assumes different forms depending on the volume of each fluid present and on the velocity. The design and operation of a two phase steam/water transmission system presents a number of problems. Most of the experimental and operational information available is limited and confined to comparatively short pipelines. The calculation of pressure drop, which is vital for determining

the pipe diameter, is much less precise than for either steam or water flowing in separate pipes although an approximation can be made by use of data developed primarily for oil/gas mixtures. The pressure drop due to friction will be greater for a steam/water mixture than for the same quantity of steam only in an equivalent pipe. Added to this are the rather indefinite pressure drops which will occur at bends, tees, manifolds, etc. [79].

In general, steam transmission lines must provide for plant variations in load. Although steam lines could be built that would withstand the shut-in pressure of the reservoir, it is better reservoir management to allow the steam to escape through pressure control devices. This practice prevents widely fluctuating flow rates at the formation face which would cause dirt and formation fines to be jarred loose and produced with the steam. Separating equipment capable of removing moisture and fine particulate matter must be provided in the gathering and transmission lines. Proper sound-muffling devices that provide the required attenuation must be installed on bleeds, stacks, and blowdown vents [81].

Oil, gas, coal can be moved everywhere without a loss of energy, but steam and hot water lose temperature in moving. It is estimated that with a good insulated pipe system, a loss of 0.5 to 1.0 percent of the energy per km seems reasonable figure for a steam pipeline system. It is considered that 10 km is maximum distance between a steam well and the power plant.

In the space heating, the economic distance from the wells to the utilization plant is greater. Space heating is a suitable market for geothermal water at temperatures below 100^{o}C. Moreover, high temperature water is more suitable for long distance piping than steam [82]. In Iceland, the hot water is carried for a distance of over 35 km [85].

5. Corrosion and scaling

The major problems in geothermal engineering are corrosion and scaling caused by transmission and collection of geothermal fluids. Corrosion in pipelines is most severe when oxygen gains access to the system and cooling towers as a result of the oxidation of hydrogen sulphide contained in the condenser. The deposition of silica scale may occur because of a temperature drop in the geothermal fluids; the deposition of carbonate scale, on the other hand, occurs when the pH changes in response to the escape of dissolved gas as pressure is reduced. The exclusion of air from the system can prevent corrosion. The deposition of silica and carbonate scale can be controlled either by maintaining carbon dioxide in solution by pressurizing the fluid, or by allowing deposition is specially constructed settling tanks from which it can easily be removed. Investigations on corrosion by geothermal fluids, steam, and condensates indicate that the martensitic stainless steels and copper-base or nickel-base alloys are very susceptible to corrosion. However, the austenitic stainless steels, ferritic stainless steel, and lead-clad carbon steel exhibit high resistance to corrosion [35].

In general, oxygen-free thermal water is not corrosive to steel or concrete and does not precipitate scale. However, traces of oxygen absorbed by the water initiate corrosion and scale forming in pipes and radiators. As it is difficult to keep the circulating thermal water completely free of contact with air, a dilute solution of sodium sulphite is added to the water in order to reduce traces of oxygen. The thermal water is corrosive to copper-base and nickel-base alloys; mild steels show sufficient corrosion resistance to permit economical use for heavy equipment.

At some sources, the geothermal water is not suitable for direct use in heating systems, and indirect heating is the rule. Difficulties are reported with steel or cast iron thermostatic valves resulting from impurities in the water; nonferrous-type fittings corrode rapidly.

Chlorides, hydrogen sulphide, carbon dioxide, and steam wetness are believed to be the most significant factors governing corrosion by the well fluids.

Various tests indicate that, although corrosion needs to be considered in design and operation of equipment handling well fluids, the utilization of the steam with equipment in commercially available alloys will be quite practicable [8 & 80].

There are three temperature ranges with different phenomena:

First, water produced by springs or wells at a temperature below 60°C is not harmful even if it has had contact with air and has absorbed some oxygen. A slight scale may be precipitated in radiators after a decade or two.

Second, water issued in the range 60°C to 100°C generally causes very little corrosion and does not precipitate much scale if free of oxygen. However, contamination with air may result in a rather rapid scaling, e.g., clogging of radiators after a period of a few years. The scale appears to be formed by a corrosion of the steel piping. Steel-plate radiators appear especially vulnerable and should not be used in any heating system with direct use of the geothermal water.

Third, water issued at 100°C or higher temperatures contains silica in excess of 150 ppm. Water of this type may precipitate scale rather rapidly and should not be used directly.

However, the mixture of water and steam issued by wells, in the high-temperature geothermal areas does not appear to cause much corrosion of equipment made of steel. The external corrosion of the equipment is more of a problem and special care should be taken in preventing leaks.

Some geothermal waters in Iceland are contaminated by sea water and contain several hundred ppm of sodium chloride, and as such are more corrosive than the ordinary geothermal waters [8].

It is important to mention the problem of silica and calcite deposition, since such incrustation reduces the rate of flow of the fluids. Silica is precipitated from surface flows with water at temperatures under 100°C. Some waters are exceptionally high in SiO_2. The solubility of amorphous silica is about 350 ppm at 100°C, and probably 500 ppm at 150°C.

Deposition is considered to occur only when the silica content exceeds the solubility limit of amorphous silica as a result of the cooling and evaporation caused by the evolution of steam. In that case the polymeric forms of silica are suspended in the solution and deposit a film on the surface. The growth of quartz crystals appears to be too slow for the less soluble form of stable silica to form deposits in the casing, even though it does deposit in the rock of the hottest zones.

As for calcite, it is known that the total concentrations of calcium and bicarbonate in thermal waters are usually high enough to cause calciting problems. Calcium carbonate is deposited in hydrothermal sources of pH 6 to 8, when the dissolved calcium exceeds a few ppm. The production of fluids at intermediate pressure can avoid the precipitation of carbonates in depth. Silica deposition gives serious trouble in waters with over 350 ppm of SiO_2 [14].

The geothermal steam and high temperature water found in volcanic areas are contaminated with chemical impurities of underground origin, and during their utilization they may be further contaminated with impurities from the atmosphere. These impurities introduce corrosion problems which must be controlled in the design and operation of geothermal plants. In addition, the release of these impurities to the surface environment may introduce associated atmospheric and surface water corrosion problems.

The most common impurities encountered in geothermal fluids are: silica, chloride, fluoride, borate, sulphate, carbonate, sodium, potassium, lithium, calcium, magnesium, ammonium, hydrogen sulphide, carbon dioxide, and hydrogen chloride.

These nongaseous impurities such as sodium chloride, are usually removed by separation and/or scrubbing in the water phase before utilization of the steam phase in power generation or heating systems. The gaseous impurities such as H_2S which remain substantially in the steam phase, are usually accompanied by residual traces of the nongaseous impurities. After utilization and/or condensation of the steam the gaseous impurities become concentrated, contaminated with atmospheric oxygen, and may be released to the atmosphere.

In this way, the nongaseous impurities are usually of major significance in water-phase corrosion in geothermal systems, while the gaseous impurities are usally of major significance in steam phase, condensate, and atmospheric corrosion.

The main possible interactions between these chemical factors, physical factors such as temperature and stress, and the various materials of construction present the main problems of corrosion control in the design and operation of systems for the utilization of geothermal fluids.

The basic corrosion phenomena encountered in plants utilizing geothermal fluids may be discussed under the following headings:

Surface corrosion attack resulting in general surface wastage or pitting of usually metal or concrete surface, has been investigated in various countries of direct engineering measurements, use of the ASTM sample method and by corrosometer probe techniques. Surface corrosion may be extremely severe in geothermal fluids containing free hydrochloric, sulphuric or hydrofluoric acid prohibiting the practical use of such fluids. However, most of the significant geothermal energy resources explored to date are not as highly contaminated with mineral acids, and provided the fluids are not

contaminated with atmospheric oxygen, surface corrosion rates of common structural materials are sufficiently low to permit their practical use.

Detailed surface corrosion rates based on general conclusions may be drawn in the following:

- in air-free geothermal steam and high-temperature water, corrosion rates of the common engineering alloys are usually higher than those encountered in clean boiler plant steam and water under similar temperature and pressure conditions,

- corrosion rates of most common engineering alloys in air-free geothermal fluids, with the possible exception of copper-base alloys, are low enough for their practical use in the construction of geothermal plants,

- aeration of geothermal media drastically accelerates the corrosion rate of most engineering alloys, with the notable and useful exceptions of austentic stainless steel, titanium, and chronium (plating). The depolarizing action of oxygen introudced by aeration offers an obvious explanation of this acceleration,

- little published information is available on the corrosion performance of nonmetalic materials in geothermal media. Concrete and grout are widely and satisfactorily used and perform well except under conditions where atmospheric oxidation of H_2S can produce sulphate attack. Epoxy surface coatings on steel have also provided adequate protection against corrosion by aerated geothermal media,

- surface corrosion of carbon steel and galvanized steel becomes severe in atmospheres contaminated by saline spray from geothermal bores, requiring the use of aluminum, stainless steel, or protective coating if the contamination cannot be avoided. Surface tarnishing of copper and silver is also very rapid in atmospheres contaminated by H_2S, and may

become significant in electrical, telephonic, and building rainwater equipment. However, aluminum is not tarnished by H_2S.

Surface corrosion information of this type, illustrated in the table below, can be usefully applied in selecting materials for specific items of equipment to utilize geothermal fluids, and in indicating operating precautions needed to control corrosion. For example, for prevention of air leakage into low pressure turbine, the use of protective coating or resistant alloys in jet condenser bodies and condenser gas extractors where aeration in unavoidable, and precautions against standly corrosion in shut-down plants, are usually necessary to minimize surface corrosion damage.

Metal	Bore water[1] > 200 °C	Water[3] ~ 125 °C	Steam[4] 100-200 °C	Aerated steam[5] ~ 160 °C	Condensate[6] ~ 70 °C	Condensate/fresh water mixture[7] ~ 50 °C	Highly acid thermal water[8]
Titanium	0	0	0	0	—	—	0
Chromium (plating on steel)	0		0	0	—	—	—
Aluminum	I	0.8-P	0-P-1	0	0.2	9	28
Zinc (coating on steel)	S[14]	1	0-1-P	S	—	S	—
Austenitic stainless steels[9]	0.1	0	0	0	0	0	22
Ferritic stainless steels[10]	0-0.1	0.1-P	0-0.3-P	1-P	0.1-P	0-0.5	—
Carbon and low alloy steels	0.3-0.4	0.3-0.5	0.3-6	20	3	30-170	1,000
Grey cast iron	1	0.4	1-3	10	—	90	—
High silicon cast iron	—	—	0.5	1	—	—	8
Brasses[11]	5	0.3	0.3-0.6	40	0.2	—	—
Bronze	20	—	2	9	—	—	—
Aluminum bronzes	10	—	2-3	10	1	—	—
Silicon bronze	—	—	3	20	—	—	—
Cupronickel	9	—	2	—	—	—	—
Beryllium copper	10	—	4	—	—	—	—
Copper	20	10	2	40	5	—	—
Nickel	6	—	1	8	2	—	—
Monel and K Monel	8-10	1	2-4	10	4	—	14
Nimonic 75	0.3	—	0	—	—	—	—
Inconel	1	0	0-0.3	80	—	—	20
Lead, antimonial lead	—	—	0.5	2.5-P	—	1	6

1. 1 mil = 0.001 inch.
2. Tests in water at bottom of a closed geothermal bore.
3. Water separated from wet geothermal steam at wellhead.
4. Steam separated from discharging geothermal bore.
5. Geothermal steam mixed with injected air.
6. Geothermal steam separated and condensed under pressure.
7. Geothermal steam condensed with fresh water to stimulate fluid in a jet condenser hot wall.
8. Natural water in a volcanic crater.
9. 18/8 CrNi, 18/8/3 CrNiMo and 18/12/2 CrNiMo varieties.
10. 13 Cr, 17 Cr, 17/2 CrNi varieties.
11. 60/40 CuZn, arsenical 70/30 CuZn varieties.

I = internal attack with embrittlement.
P = pitting.
S = zinc coating stripped.

Erosion - corrosion, a conjoint action of erosion and corrosion on metals, is significant in some items of geothermal plants. Erosion-corrosion of turbine blades by wet steam at high velocity is particularly important in affecting the design and efficiency of steam turbines.

Empirical tests in geothermal steam have shown that 13% Cr stainless steel blading alloys possess adequate erosion-corrosion resistance for geothermal steam service at 9% wetness and 900 ft/sec. They have also shown that under these conditions erosion-corrosion resistance of metals is directly related to their static corrosion resistance in the same media, and not to hardness as was normally assumed. Thus improved resistance to erosion-corrosion would be expected from the more corrosion resistant alloys such as austenitic stainless steels and titanium.

A more unusual variety of erosion-corrosion may be encountered in electrical commutators where tarnishing of the copper surfaces by atmospheric H_2S contamination from geothermal steam may accelerate wear of the commutator surface at the zone of contact with the carbon brushes. The elimination of H_2S contamination reduces commutator wear to normal rates.

Stress corrosion and sulphide stess cracking, as reported by several investigators, occurs in hot chloride solutions, usually concentrated solutions above 100°C and under conditions where oxygen was not deliberately excluded. From laboratory tests and plant experience, 5 ppm of chlorides and 50°C have been suggested as minimum requirements for stress corrosion.

Several investigators have reported this type of cracking in wet, chloride-contaminated steam, and in geothermal steam. High temperature water has shown that even under severe applied stress, austenitic stainless steels are not susceptible to stress corrosion in air-free geothermal fluids. The stress corrosion requires the presence of oxygen in addition to the other necessary factors, i.e., the presence of chloride solutions at high temperature

and tensile stress. In addition, dissolved oxygen is an essential agent for stress corrosion of austenitic stainless steels in chloride solutions.

Various investigators have reported stess corrosion cracking of some nonferous alloys in geothermal fluids. These alloys are of minor importance in geothermal plants and can be replaced by alternative resistant alloys.

Environmental stress cracking of nonmetallic materials. Embrittlement and cracking of plastic materials (usually known as environmental stess cracking), such as flexible PVC tubing, polyethylene, rubber, etc., has been experienced in New Zealand geothermal fields.

Sulphide stress cracking, based on plant experience and extensive laboratory research, has shown that high strength steel is susceptible to sulphide stress cracking, i.e., to spontaneous fracture when simultaneously stessed and exposed to aqueous solutions of H_2S. There is abundant data on sulphide stress cracking in H_2S solutions below 100°C, but much less information on the action of H_2S solutions at higher temperatures. Geothermal fluids frequently contain H_2S, hence it is not surprising that sulphide stress cracking in geothermal steam and high temperature water has been mainly reported based on tests with constant-deformation stress corrosion specimens.

Sulphide stress cracking is a factor of major importance in the design and operation of equipment, particularly turbines, for the utilization of geothermal steam and water. The use of low strength (less than 88,000 psi) steel is known to be safe for use in steam media under reasonable service stresses.

Hydrogen infusion. Several investigators have shown that corrosion by aqueous solutions containing H_2S causes infusion into steel. Hydrogen infusion is known, under favorable circumstances, to cause blistering and embrittlement of steel, and to be associated with sulphide

stress cracking and delayed fracture of stressed steel. In geothermal fluids blistering of steel appears to be observed only rarely in grossly laminated steel. Hydrogen probe tests have provided more positive evidence of hydrogen infusion.

Hydrogen-induced delayed fracture. Several tests have shown that hydrogen infusion can produce delayed fracture in high-strength steel subjected to tensile stress. In addition, hydrogen infusion results from exposure of steel to geothermal fluids. Hence delayed fracture of tensile-stressed, high strength steel would be expected during exposure to geothermal fluids. There are indications that sulphide stress cracking, delayed fracture, and hydrogen infusion are interrelated phenomena.

Corrosion-fatigue. Several test have drawn attention to the harmful effects of simultaneous corrosion on the fatigue life of metals. Similar harmful effects on fatigue properties would be expected from corrosion by geothermal media and could be of significance in the design and operation of steam turbines. Unusually severe corrosion fatigue is encountered in salt solutions containing dissolved H_2S similar to fluids which may be encountered in geothermal fields. Experience with fatigue failure of blades in turbines operated in New Zealand geothermal steam suggests that corrosion fatigue is operative, but can be controlled by careful turbine design [86, 91].

The purity of the steam produced in a nuclear chimney or surrounding fracture zone will have a major effect on the design, cost, and operation of a nuclear-stimulated geothermal power plant. Both the quantity and the type of contaminants carried by the steam may affect the well life, the turbine-condenser design, the operating efficiency of the plant, and the safety and environmental protection regulations.

The problems that can result from mineral deposition on the piping, in the steam turbine, and in the condenser of a nuclear stimulated geothermal power plant can be extremely serious. The deposition of salts and silica (and hence of associated radioactivity) on turbine blades

is dependent on the impurities in the steam and on the steam pressure. Salt deposits on steam turbine blades are water-soluble and, with proper operating procedures, can be washed off with water. The more important of these salts are NaCl, NaOH, sodium silicates, Na_2CO_3, and sometimes Na_2SO_4. Deposits that are insoluble in water are most commonly silicic acid, amorphous silica, and various crystalline forms of silica. Water insoluble deposits of iron oxides and $CaCO_3$ may also occur.

The water insoluble deposits, particularly the various forms of silica, present the most serious problems. These deposits can lead to the distortion of turbine blade configuration and hence lower turbine efficiency. More seriously, they can lead to turbine imbalance and ultimately to vibrations that can materially damage the turbine. It may be possible to wash the water-insoluble deposits with NaOH solutions if the rate of deposition is not high, but the operation is time consuming and requires considerable care if damage to the turbine is to be avoided.

If geothermal steam from a nuclear chimney is to be directly used in turbine operation at high pressure, it will most likely need purification in order to prevent inefficient turbine operation and excessive radioactivity build-up. A suggested method of purification is to scrub the steam with high-purity water before passing it through the turbine. Unfortunately, such a process cools the steam, degrades its energy, and lowers efficiency. Also, after scrubbing, the steam is at its saturation point, and its use in the turbine could lead to erosion of the turbine blades by the impinging of water droplets. In addition, the steam would need to be reheated.

Other alternatives warrant consideration. A solid-phase scrubber such as limestone might prove effective in removing silica. Another approach is to add a heat exchanger in which water or other secondary fluid (e.g. isobutane) would be boiled and the steam from the nuclear chimney condensed. Though this additional equipment would decrease the thermal efficiency of the process, it would concentrate the scaling and radioactivity.

If scaling in heat exhangers proves severe, either a second heat exchanger could be provided, or chemical and/or mechanical descalers could be added. If the steam is cleaned, two contaminants will be present in the scrubbing system, but if a fluid scrubbing system is used, it might be possible to dispose of the radiactivity and contaminants present in the system by reinjection into the nuclear chimney.

The following are the radioactive contaminants that might be volatile in steam after 180 days from either fission or thermonuclear explosives: the fission products are $^{85}Kr^*$, $^{103}Ru^*$, ^{106}Ru, $^{106}Rh^*$, $^{125}Sb^*$, $^{127m}Te^*$, and $^{137}Cs^*$; the induced activities are ^{3}H, $^{22}Na^*$, ^{33}P, ^{35}S, ^{37}Ar, and $^{134}Cs^*$ (significant gamma emitters carry asterisks). For 1 Mt of yield, the amount of gamma radiation remaining after 180 days of decay is 3.0×10^{16} MeV/sec for an all-fission device and 1.1×10^{15} MeV/sec for a thermonuclear explosive employing 3 kt of fission. Although the thermonuclear explosive shows a lower level of gamma radiation for volatile radionuclides, it has a very high level of beta activity in the form of tritium.

Noncondensable gases (including radioactive nuclides) that are present in the steam will be separated in the condenser. In natural steam fields, noncondensable gases are exhausted from the condenser and vented to the atmosphere. For a nuclear-stimulated geothermal power plant, the gases could be collected, and the radioactive contaminants, such as ^{85}Kr, ^{37}Ar, and ^{3}H, could be separated or concentrated, then stored underground. Low levels of volatile chemical and radioactive contaminants could be vented to the atmosphere.

Thermonuclear explosives would yield several orders of magnitude less krypton but much more argon and tritium. Once the tritium has exchanged with the hydrogen in the water or steam it would be most difficult to remove, and adequate measures to ensure its safe containment would be needed.

To evaluate the corrosive behavior of noncondensable gases in geothermal steam, an assessment must be made of the impurities present

in the rocks and source waters of the wells. It may then be possible to derive some conclusions concerning the condensable and non ondensable impurities picked up by the steam and the chemical effects of these impurities on the steam-turbine system. Much of the information on corrosion and scaling is based on experience with natural geothermal wells. Caution must be exercised in extrapolating this information to the nuclear case, since different steam conditions and geology may prevail for the nuclear wells.

Substances known to cause corrosion are present in significant amounts (see table below). Similar substances may be anticipated for the nuclear case. Whether or not corrosion and scaling reactions actually occur depends on the specific conditions in each case. Chlorides, NH_3, CO_2, and H_2S are known to be corrosive to metals in certain instances. Steam and hot water are corrosive to all silicate materials, such as grouting in pipe joints, reinforced concrete pipes or tanks, and silicate filter beds. All such materials should either be avoided or protected with suitable coatings. Scaling (or deposition) may occur in pipes, turbines, or condensers as a consequence of volatile impurities in the steam, such as the chlorides, hydroxides, carbonates, sulfates, and silicates of the alkalies, calcium carbonate, and silica. Noncondensable impurities in the steam, such as

Chemical Analyses of Noncondensable Gases in Geothermal Steam

Site	Maximum source temperature, °F(°K)	Wellhead temperature, °F(°K)	Noncondensable gas content of total discharge (wt %)	Mole percent						
				CO_2	H_2	H_2S	CH_4	NH_3	N_2	Residuals
Hengill, Iceland	446 (503)	~320 (433)	0.3	84.6	2.1	4.9	0.0	—	—	8.4[a]
Hveragerdi, Iceland	446 (503)	~320 (433)	0.1	78.5	1.1	17.2	—	—	—	3.2[a]
Krysuvik, Iceland	446 (503)	~320 (433)	1.3	83.9	5.4	9.6	0.1	—	—	1.0[a]
Wairakei, New Zealand	509 (528)	~383 (468)	0.01–0.5	93.0	0.8	3.8	0.8	~0.2	1.4	—
Waiotapu, New Zealand	563 (568)	—	0.07–0.2	90.0	1.5	7.8	0.3	~0.2	0.2	—
Larderello, Italy (1870)	—	—	—	90.5	2.0	4.2	1.4	—	1.9	—
Larderello, Italy (1960)	473 (518)	~374 (463)	4.5	92.4	1.4	2.5	1.0	1.7	0.6	0.4[b]
The Geysers, California	>401 (478)	347 (448)	0.7	69.3	12.7	3.0	11.8	1.6	1.6	—
Showa-shinzan Volcano, Japan	—	381 (467)	0.6	69.4	12.4	3.9	0.1	0.0	9.1	5.1[c]
Showa-shinzan Volcano, Japan	—	622 (601)	2.2	84.9	6.6	1.0	0.1	0.0	5.2	2.2[c]

[a] Includes N_2.
[b] Primarily H_3BO_3.
[c] Primarily HCl, with lesser amounts of HF and SO_2.

CO_2, H_2S, H_2, and CH_4, may not necessarily be corrosive, but will need to be exhausted from the turbine discharge in order to have an efficient turbine operation.

Although a wide variety of corrosion mechanisms has been identified, the most serious in alloys is probably stress corrosion. It is known that stress corrosion can be induced by trace amounts of either chlorides or sulfides, and can lead to formation of fissures and fractures in a variety of alloys used in the construction of turbines. A minimum concentration and temperature requirement for chloride-stress corrosion is belived to be 5 ppm of chlorides of 50°C. The presence of oxygen accelerates the rate of stress corrosion. There is no limiting stess below which cracking will not occur. Sulfide-induced stress cracking can occur in the presence of H_2S at temperatures up to at least 190°C. The gas H_2S also causes a phenomenon known as hydrogen infusion, which can lead to the embrittlement, blistering, and fracture of stainless steel.

Other corrosion mechanisms that should be mentioned are chemical corrosion and mechanical erosion. Chemical corrosion can occur from the presence of NH_3, H_2S, CO_2, and chlorides in geothermal steam. Generally, the corrosive action of these chemicals is enhanced by the presence of air. Chemical corrosion has been minimized or avoided in most natural geothermal power plants by the proper selection of alloys and by avoiding aeration. At the higher steam pressures and temperature proposed for the nuclear application, however, chemical corrosion may be a more serious problem.

The problem of mechanical erosion is encountered when wet steam at high velocities impinges on the turbine blades. Such impingement can lead to a combined corrosion-erosion process that can seriously damage the turbine blades. A certain amount of success has been achieved in erosion resistance through the use of 13 Cr -- stainless steel alloys.

The experience gained with corrosion and scaling in natural geothermal power plants makes it apparent that similar problems are likely to be encountered in the nuclear case. These problems can be explored more fully by performing exposure tests on alloy samples in geothermal steam and water under the proposed nuclear application conditions. It is important in such tests that the compositions of the steam and the water be representative of the particular geothermal formation. Steam taken directly from a nuclear well would be most desirable, or lacking an actual well, it may be possible to infer the expected impurities in the steam from analyses of core samples from the formation [90].

6. Environmental effects

Geothermal developments are unique in the sense that all activities related to the power production are localized to the immediate vicinity of the power plant. For this reason the environmental effects are site dependent in origin. Certain undesirable effects, such as the production of hydrogen sulfide gas, can extend for several miles from the field and thus introduce environmental problems into the surrounding region.

Potential environmental effects that need to be examined are gaseous and particulate emissions, land modification, subsidence, seismic hazards, surface and ground water pollution, biological effects, noise effects, and sociolological effects. Therefore, research should be directed toward an accurate determination and evaluation of the character and magnitude of these effects [6].

Geothermal steam is remarkably low in atmospheric pollutants. There is no fly-ash, nitrogen, sulfur oxides, and radiation hazards. The only significant environmental hazard in geothermal power production is the effect on water quality of improper control of excess geothermal steam condensate. Natural steam is almost entirely pure water, but small amounts of other gases are liberated and produced along with the steam. The noncondensable gas content varies from an average of 0.5 percent at the

Geysers field to an average of 4 percent at Larderello, Italy. The noncondensable fraction usually runs about 90-percent carbon dioxide, the rest being mainly methane, hydrogen sulfide, and ammonia. Although these gases are vented from the condenser into the atmosphere, they are not considered an environmental hazard because of their low concentrations and because of the remote locations of the plants.

Hydrogen sulfide presents a potential problem with the enlargement of geothermal installations. It can be chemically extracted from the noncondensable gas and converted to elemental sulfur, which is common practice in many natural gas fields.

The steam condensate carries trace amounts of detrimental substances, mainly boron and ammonia, which if released into surface drainages would affect downstream water quality. At the Geysers field the surplus condensate, which totals about 20 percent of the total fluid produced, is reinjected back into the producing reservoir [78].

The other type of geothermal effluent, more frequently encountered, in the hot brine, and a typical example of this is the geothermal field of the Imperial Valley - Mexicali area. The brine contains from 20,000 ppm (Cerro Prieto) to 250,000 ppm (Niland) of dissolved salts. It is apparent that this amount of dissolved solids will present engineering problems in the energy-to-power conversion cycle. These problems can be solved at least at the lower solids level, was demonstrated in Wairakei (New Zealand) and Cerro Prieto (Mexico). However, the means of the residual brine disposal used there by discharging it into the ocean or into evaporation ponds will not be applicable to the Imperial Valley field.

It is suggested that, in view of the initial high enthalpy of the Imperial Valley brine, there is sufficient energy left in the brine after 20% of it is flashed into steam (for power extraction) to permit its use for a desalination process. It has been estimated that, in this case, about 5 to 7 million acre-feet/year of low salinity water could be used to relieve the

salinity problem of the Colorado river and to improve the irrigation of the Imperial Valley - Mexicali area [84].

The main types of pollution likely to be encountered are atmospheric from the disposal of gases, thermal from the waste heat, and chemical from the dissolved salts in the waste water. One or more problems arising from the effects of pollution is likely to be encountered in any geothermal field. The extent and detailed nature of the problem will vary considerably for each field. In general, the quantities of gas discharged are relatively small, and atmospheric pollution is not a serious problem provided the gases are vented at a height above that of structures in the vicinity. However, care must be taken to avoid dangerous accumulations of gas arising from leakages in the steam or hot water systems. Ventilation should be provided in all potentially dangerous areas.

Thermal pollution can be a problem when local rivers or streams are used for disposal of the waste water. Fish life may be affected, and the growth of water weed encouraged. This is a complex problem with many interrelated factors.

The problems arising from chemical pollution can be so serious enough to prevent or hinder the development of an otherwise promising field, as has been the case with the Alton Sea field in Southern California, USA. At Wairakei, New Zealand, the dissolved salts are low and the waste water is discharged into a major river with minor problems. Another example is Ahuachapan in El Salvador, where, among other problems, the wells cannot be discharged vertically because of the damage that would result to the coffee plantations in which the wells are located. Solutions which have been proposed for the problem are recovery of the chemicals, reinjection of the waste water into the production field or pumping into the sea. The solution may be costly, but there may also be other economic or technical benefits.

Chemical pollution is normally a relatively minor problem in fields producing steam. However, the pollution by boron and ammonia is now requiring preventive treatment at The Geysers, California, US. The solution adopted here is the injection into the reservoir of the condensate containing the pollutants [13].

<u>Chemical deposition.</u> Reduction of output due to chemical deposition in the wells has occurred in several fields, but removal of the deposits has been a direct process and in most cases the output has been fully restored. Deposition normally takes place at the boiling level in the well, as pressures decline due to exploitation, it becomes progressively deeper. Ultimately, boiling and deposition will take place in the formation producing a detrimental effect.

Chemical deposition can also be a problem in the disposal of waste water. At Waizakei, New Zealand, silica deposits in the waste water channel must be removed annually. However, at the Otake field, Japan, a pipeline carrying waste water was rendered useless after a relatively short operation due to chemical deposition [13].

The environmental impact of any power production system is reflected in the number and complexity of the steps in the fuel and production cycle. Because geothermal power plants utilize natural steam, they don't need any complex steam generating equipment or extensive mining, processing, storage, or transportation facilities, as do other power plants.

The chief impact from the geothermal power occurs during the period of field development and construction of the steam gathering lines and power plants. The impact is limited to the area of the field and poses little disruption of the landscape like that connected with mining the fuels for other power plants. During the productive lifetime of the geothermal field, which can extend over many decades, most of the area can be used for other purposes. At Larderello, Italy, for example, where natural steam has been used to produce electricity for 60 years, farms, orchards, and vineyards cover much of the land surface.

Natural steam does contain a small percentage of noncondensable gases that are vented to the air. But compared to the amounts dissipated by fossil fuel plants, these gases mostly carbon dioxide, nitrogen, hydrogen, methane, and hydrogen sulfide are minor. Compared to the total gaseous release from all steps in the nuclear-fuel cycle, the overall volume and toxicity of gases from the geothermal plant is, again, minor.

Dry steam geothermal developments pose no hazard to water supplies. Moreover, dry steam and flash steam power plants supply their own cooling water by condensing their steam, and are therfore independent of the sources of condenser cooling water that are needed by other types of power plants. Hot water geothermal systems will have an effect on the waters, but in most cases it will be bringing waters into use that are below the economic drilling depths of waters currently in use [94].

However, there are manifold environmental aspects of geothermal extraction stimulated by nuclear explosives.

The pre-plant operations, though of relatively short duration compared to the lifetime of the geothermal site, are the most environmentally significant and present the greatest potential impact. This period includes complete site studies and testing using the evaluations to determine the feasibility, safety, and potential consequences of stimulation by nuclear explosives.

The environmental effects of nuclear explosion itself include the potential release of radioactivity to the atmosphere and to ground water. In addition, for any underground nuclear explosion the possibility of seismic damage to natural formations and to man-made structures must be evaluated. The explosive seismic shock might also cause small natural aftershocks in the local vicinity or trigger natural volcanic eruptions and hydrothermal explosions.

During plant operations phase, the environmental aspects of interest are the leakage of radioactivity and the distribution of radioactive materials in the biosphere. The possible loss of fission products into moving water systems and the appearance of radioactive materials in food chains will demand a continuing program of sampling to evaluate the transport of radioactive materials through ecological systems. The effects of nonradioactive plant effluents and emissions and their environmental consequences are also to be considered. Because the primary working fluid is radioactive, the consequences of credible plant accidents, particularly those involving coolant loss are significant [67].

Noncondensable gases present in the steam of a thermal electric plant tend to collect in the condenser. In natural fields these gases are generally eliminated by venting to the atmosphere. In a nuclear-stimulated geothermal system the operational venting of large quantities of gases with radioactive components might be unacceptable, and it would be necessary to monitor the effluent. If the radioactivity exceeds the established maximum concentration, the radioactive components must be compressed and stored or recycled into the cavity.

After the useful production of energy has ceased, certain controls and safeguards would have to be maintained to ensure continued public safety and ecological compatibility. Because of the longevity of many of the radioactive isotopes produced within the nuclear cavity (e.g. Kr-85, Cs-137, tritium, Sr-90, plutonium, Ce-144, and Ru-106), a quasi-perpetrual program of monitoring and control of radiation losses from the cavity and of other contaminated facilities should continue [92].

7. Economics

For any heat intensive process such as space heating, power production, distillation, hot water supply, refrigeration, air conditioning, and certain manufactures it is very important that cheap heat be available. Geothermal energy can provide one of the cheapest source of heat, without

prejudice to the other cost components which together account for the cost of the end product, i.e., capital cost of the necessary plant and equipment, the cost of raw materials fed into the process, attendance and maintenance costs, etc.

The development of geothermal energy usually requires fairly heavy initial expenditure on exploration before the geothermal fluids start to flow in worthwhile quantities. If geothermal energy is to compete with fuel as a source of heat it must be clearly demonstrated to be cheaper than the alternative after bearing its full share of these exploration costs.

The cost components that enter the reckoning of geothermal heat costs, based on 1973 estimates, may be listed as follows:

Exploratory costs. Three geothermal exploration projects in the Middle East and in Latin America have been financed in recent years by the United Nations Development Program Special Fund, and that the cost of these has averaged less than \$3 million each, they have covered a wide range of investigations and a moderate amount of exploratory drilling. A further exploration planned, but not yet executed in the Far East has been estimated at \$2.5 million. Based on other estimates, a figure of \$3 million may therefore be regarded as a conservative estimate for geothermal exploration. It is further assumed that the whole amount of this sum is borne by a single developed zone. Spreading this cost over the assumed number (50) of bores, the exploration costs may thus be expressed at \$60,000 per bore.

Drilling costs. These costs must depend on the nature of ground drilled, on its location, on the depth of the bores, and on the scale of operations. Considering that the average cost of oil wells in recent years having an average depth of 3,854 ft, has been just over \$50,000 per bore. The depth of geothermal bores is usually about 2,500 ft and that drilling is more expensive than oil drilling; a cost per well of \$60,000 would be a

cautions figure. Assuming further that of every three bores sunk, only two are successful and the third is a failure (in California and New Zealand a much higher success ratio has been achieved). The cost per each successful bore may be about $90,000.

Wellhead equipment costs. To cover the cost of a separator, silencer, valving, integral pipework and a reasonable degree of instrumentation (pressure gages, thermometers and flowmeters) an average figure of $35,000 per borehole would be reasonable.

Collection pipework costs. This is a very difficult figure to estimate rationally, as it can vary enormously from field to field. Based on the number of boreholes, quantity of fluid to handle, steam velocity and pressure, the number of pipes and diameter is computed. To this should be added the lagging, expansion facilities, traps and suitable valving, reaching an average cost of $90 per foot. To this must be added the cost of the terminal equipment, such as pumps, head tank, flashing equipment and control gear which, based on the experience of the Wairakei experimental hot water transmission, may be valued at about $3 million. Hence, the total hot water transmission costs may be estimated at:

pipelines and branches		$2,700,000
terminal equipment		$3,000,000
	Total	$5,700,000

Adding to this the cost of the steam transmission, a total heat transmission cost arrived at is $13,200,000 or $264,000 per borehole.

Theoretical recurring costs may be estimated as follows:

Capital charges. Interest charges will be taken at various prevailing rates. Depreciation or amortization costs may then be estimated on a sinking fund basis for each rate of interest according to the assumed

lives of boreholes for 10 years, and wellhead gear and collection pipework for 25 years. There is usually a tendency for a borehole's output of heat to decline in time to rates which vary from field to field but which may be on the order of 5% to 10% per annum.

Borehole replacement costs. In assigning a life of only ten years to the borehole, the actual cost of the borehole replacement as such would be covered by the sinking fund provisions. However, when a borehole falls out of use and has to be replaced in order to maintain the required total heat yield, certain incidental expenses are incurred. Although the same separator, silencer (pump), and instruments may be transferred to the new site, costs will be incurred in moving these pieces of equipment and in modifying the shape of the pipework. It would be advisable to allow a figure of $15,000 for this adaptation per new borehole.

Operation, repairs and maintenance. An allowance of 2% per annum would be a reasonable figure for covering attendance, repair, and maintenance of wellhead equipment, pipework, pumping and control equipment and instruments. The actual boreholes themselves should not theoretically require any repairs or maintenance, but blockages may sometimes occur which must be cleared, and casing can become damaged. A similar allowance of 2% per annum would be reasonable for such repair and routine inspection.

Cost of heat at the boreholes. On all these assumptions it is now possible to assign an approximate value to heat as it issues out of boreholes in the field. The supporting calculations are detailed in the proceeding table for various interest rates. Two sets of figures have been deduced, for 100% and 90% load factor. The 100% is based on the assumptions that the heat flows continuously from a borehole and can be used without interruption throughout the year. The 90% is assumed that for 10% of the time each borehole is taken out of service. Experience shows that, for power generation at any rate, a borehole load factor of 90% is quite realistic. The costs have also been deduced on the alternative assumptions that only the steam is used and that the heat of the total fluid is used.

Interest rate		5%	6%	7%	8%	10%
		$p.a.	$p.a.	$p.a.	$p.a.	$p.a.
1. *Interest on:*						
Exploration	$ 60,000 bore					
Drilling	$ 90,000 bore					
Wellhead equipment	$ 35,000 bore					
Total	$185,000 bore	9,250	11,100	12,950	14,800	18,500
2. *Sinking Fund:* on 25-year basis on exploration and wellhead equipment	$ 95,000 bore	1,990	1,732	1,502	1,300	965
on 10-year basis { on drilling costs	$ 90,000 bore					
on 10-year basis { on bore replacement costs	$ 15,000 bore					
	$105,000 bore	8,350	7,960	7,595	7,255	6,590
3. *Operation, repairs and maintenance:* at 2%, on wellhead equipment and drilling costs	$125,000/bore	2,500	2,500	2,500	2,500	2,500
4. Net total		22,090	23,292	24,547	25,855	28,555
5. Add 10% for *contingencies and management* costs		2,209	2,329	2,455	2,586	2,856
Grand total		24,299	25,621	27,002	28,441	31,411
		¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU
6. *Cost of heat*, based on average yields per bore of:						
6.1 at 100% load factor { Steam	115,100,000 BTU/h	2.41	2.54	2.68	2.82	3.12
Water	61,850,000 BTU/h	—	—	—	—	—
Total	175,950,000 BTU/h	1.55	1.63	1.72	1.82	2.00
6.2 at 90% load factor { Steam only		2.68	2.82	2.98	3.14	3.47
Total fluid		1.72	1.81	1.91	2.02	2.22

<u>Cost of heat at collective point of delivery.</u> By adding the capital charges and other costs arising from the fluid collection and transmission system to the heat costs at the boreholes, as deduced in the proceeding table it is possible to estimate the cost of heat at the point of

Interest		5%	6%	7%	8%	10%
		$p.a.	$p.a.	$p.a.	$p.a.	$p.a.
1. *Cost at bores*		24,299	25,621	27,002	28,441	31,411
2. *Interest* on collection pipework and associated equipment	$13.2 millions or $ 264,000/bore	13,200	15,840	18,480	21,120	26,400
3. *Sinking Fund* on 25-year basis on	$ 264,000/bore	5,530	4,810	4,180	3,610	2,685
4. *Operation, repairs and maintenance* at 2% p.a. on	$ 264,000/bore	5,280	5,280	5,280	5,280	5,280
5. Add 10% of items 2, 3 and 4 for *contingencies and management*		2,401	2,593	2,794	3,001	3,437
Total		50,710	54,144	57,736	61,452	69,213
Assume that 7½% heat losses are incurred between the bores and the point of delivery						
		¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU	¢/10⁶ BTU
6. *Cost of heat*						
6.1 at 100% load factor { Steam only [1]		4.06	4.32	4.60	4.88	5.46
Total fluid		3.50	3.73	3.98	4.24	4.77
6.2 at 90% load factor { Steam only [1]		4.52	4.80	5.11	5.42	6.07
Total fluid		3.89	4.15	4.43	4.72	5.30

1. Costs of water transmission excluded

delivery of the transmission mains - both on the basis of steam only and of total fluid, and also at 100% and 90% load factor, as before. In this reckoning it is assumed that 7.5% of the heat is lost in transmission, largely apparent as steam condensation.

Very little information relating directly to heat cost has been published, but in some cases these costs can be indirectly deduced. Actual costs for geothermal heat and geothermal power in existing geothermal fields in operation is hard to formulate because of changes in prices [95].

While the specific figures vary, there is a general agreement that the geothermal electric power costs is about the same as that of hydro-power (5 to 6 mils per KWhr) and that both are lower than fossil fuel power (7 to 8 mils per KWhr) or nuclear fuel power (9 to 10 mils per KWhr). Combining the generation of electricity with water desalination would provide further economical benefits for both geothermal and nuclear power plants.

The development costs of a geothermal field may be substantial if one consideres the cost of the well from $150,000 to $250,000 and the well average power yield of 5 to 7.5 MW (100,000 to 150,000 lb/hr of steam). Thus, for a 100 MW plant, over 20 wells would be required bringing the well cost over $5 million [84].

The size of nuclear explosives for stimulation of geothermal sources required to make the concept economically sound may be a problem. Although recent discoveries of higher temperature rock make costs appear much more favorable, the use of large devices will of course decrease power costs. But the limit of device size that can be used in the continental United States is uncertain.

Figure 17 illustrates the overall economics of a 200 MW plant as a function of the fracturing efficiency of the array and the size of the nuclear explosive. Low efficiency arrays are not attractive even with large explosive

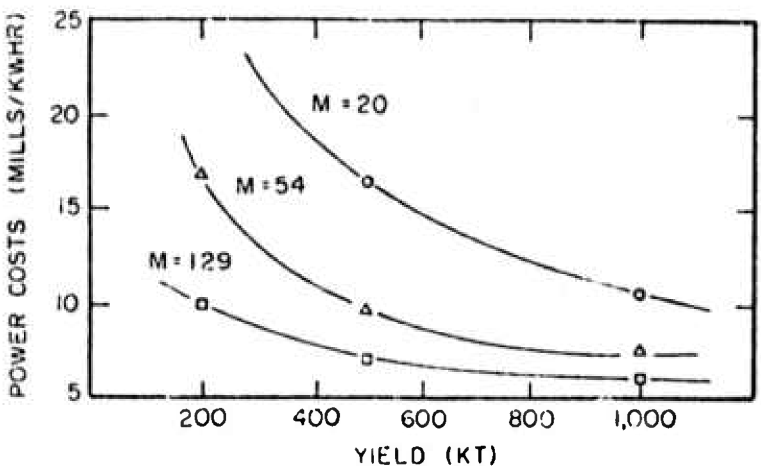


Fig. 17. Power costs from 200 MW Plowshare geothermal plant as a function of nuclear explosive yield and fracturing efficiency [96].

yield. With intermediate fracturing efficiency, the power from this plant concept would seem to be competitive at device size in the range of 500 kt and up. For higher fracturing efficiency, the plant seems to be economically competitive at nuclear explosive yield at 300 kt and greater. The use of a hotter intrusive, such as the one near Marysville, Montana, would significantly decrease these costs. They would be decreased, for example to about 5 mill/kwh for 1,000 kt devices, and with a fracturing efficiency of 54. With the same fracturing efficiency, power costs of 5.8 and 8.8 mill/kwh could be expected from 500 kt and 200 kt nuclear explosives, respectively. The economic potential of this energy source is comparable to that of most mining operations that require the fracturing of rock. In general, the economics are highly dependent on the efficiency with which the rock can be fractured [96].

Apart from the fact that geothermal heat and geothermal power may be extremely cheap, there are other reasons why geothermal fields should be developed where possible. First, even if its costs were not particularly favorable in themselves the use of a geothermal field enables an

indigenous form of energy to be used, often with consequent savings of expenditure in foreign currencies on oil and other fuels.

Evidently geothermal energy cannot solve all energy problems, because it is subject to limitations imposed by the accident of its location. There may also be occasions where the availability of a good geothermal field is nullified by problems of waste fluids that disposal cannot always be discharged into streams owing to a high content of such substances as boron, which can be highly poisonous to crops and to water supply systems. Nevertheless, geothermal heat can often be obtained without insoluble associated technical problems at costs that are far less than for any other form of heat. This fact can lead to cheap power, cheaper industry and sometimes to large savings in foreign currencies [95].

The production costs of various modes of energy generation are difficult to compare. Available data (1973), in the proceeding table are not always accurate, and may reflect different interest, exchange and taxation rate, amortization periods, special allowances, or other hidden costs and benefits.

In any case, it has been shown in Hungary, Iceland, New Zealand, and the Soviet Union that direct utilization of geothermal energy in industry, agriculture, and space heating is appreciably less expensive than the use of crude oil, gasoline, or diesel fuel for the same purposes. Natural gas, where obtainable, and coal are more nearly competitive, though still more expensive than hot water for heating purposes.

In the generation of electricity, only hydroelectric power has been found to be cheaper, and only in certain situations. In Iceland, for example, hydroelectric power was shown to be less expensive than geothermal power in most circumstances. However, the direct utilization of hot water for municipal heating is far cheaper than heating by hydroelectricity. At The Geysers in the United States, geothermal electric power proved to be

Geothermal field	Geothermal production	Local average other fuel
Electricity, U.S. mills/kwh		
Namafjall, Iceland	2.5-3.5	-
Larderello, Italy	4.8-6.0	7.5
Matsukawa, Japan	4.6	6.0
Cerro Prieto, Mexico	4.1-4.9	8.0
Pauzhetka, USSR	7.2	10.0
The Geysers, United States	5.0	7.0
Space heating, U.S.S/Goal energy		
Reykjavik, Iceland	4.6	6.7
Szeged, Hungary	3.0	11.0
Refrigeration, U.S.S/Goal energy		
Rotorua, New Zealand	0.12	2.40
Drying diatomite, U.S.S/ton		
Namafjall, Iceland	2	12

cheaper than power from other fuel sources, regardless of plant size. Even in developed countries, geothermal power compares favorably with power from very large generating stations that have the advantage of economy of scale. The ability of geothermal-generating systems to be developed economically in relatively small power units, 25 to 50 MW, is a major consideration for underdeveloped countries, where the load and the load growth are commonly small [10].

II. MULTIPURPOSE USE OF GEOTHERMAL SOURCES

Geothermal resources are entering a new phase of more intensive development through multipurpose exploitation. Most of the possible uses, whether of low or high temperature sources, appear to be economically viable and some offer great advantage in cost and convenience. Besides generating electric power, geothermal energy has broad application in the following areas: heating, hot water supply, food processing (drying, sterilization, refrigeration), chemical processing (drying of minerals, brine and syrup extraction, plastics manufacture, petroleum refining, fermentation or distillation of agricultural products, extraction of liquid oxygen and nitrogen for metallurgy), swimming pools and bath facilities, balneology, heating of soil, hot-spring irrigation, hothousing-greeenhousing, construction, and the mining of gold placers during winter months and in permafrost and frozen-ground areas [36].

Based on experience with various geothermal energy projects, it is clear that the adoption of dual or multipurpose use of geothermal sources could be economically advantageous. By combining power plants with other applications of geothermal energy it should be possible to share the costs among more than one end product.

Certain heat-consuming industries are also power-intens , in which case it may be necessary to devote a large proportion of the power generated in a multipurpose geothermal project for use within the industrial sector of the project. For example, it is found that for geothermal desalination it should be possible to generate surplus power when desalting water as long as the performance ratio is relatively low, but if large water yields are required from a bore it may be necessary to import additional power. However, the potential of a good field may considerably exceed the steam requirements of a desalination plant, in which case there may be a surplus number of boreholes beyond those required for desalination, which can not only supply the power deficit for the desalting process but can also provide a substantial margin of exportable power.

It is quite impossible to be specific in any general discussion of geothermal multipurpose projects, as each case must be examined on its own merits. But the point that requires emphasis is that whenever a geothermal field is being developed, serious consideration should always be given to applications other than power only [95].

There is little doubt that the potential geothermal energy available throughout the world is enormous, and with the technical advancement already made, there is great hope that many conveniently located areas can be successfully exploited for various application [107].

The worldwide upsurge of interest in geothermal energy was evident during the meeting (20-29 May, 1975) in San Francisco as delegates from more than 50 nations gathered for the second United Nations Symposium on the Development and Use of Geothermal Resources. Considerable changes have occurred on the world energy scene since the experts first meeting under UN auspices in 1970 at Pisa, Italy.

At the San Francisco meeting, J. J. Bradbury of the United Nations Center for Natural Resources, Energy, and Transport, stressed that increased interest in geothermal energy has extended not only to exploration in suitable locations but also to the possibilities of exploiting it in diverse forms. In addition, he noted, there has been a rapid escalation in demand for geochemists, geophysicists, geologists, and drilling engineers with expertise in geothermal exploration.

In general, a large part of the interest in geothermal energy focuses on its use in generating electricity. Total world geothermal output is currently a little more than 1000 MW, about the capacity of a single conventional power plant. Most of this comes from two major installations, one near Larderello, Italy, of almost 400 MW, and one at the Geysers, U.S., now generating 396 MW, with an additional 106 MW due to come [124].

Worldwide reserves of geothermal energy are unknown, and are the subject of much study. Estimates made in recent years are much greater than those made earlier. Several individual geothermal fields have been appraised, at least in reconnaissance form. However, for most fields only a minimum limit can be set. For example: the Ahuachapan, El Salvador, is believed to have a minimum potential of 100 MW (30 MW are planned for construction), one estimate of maximum potential for Cerro Prieto, Mexico, is 1000 MW (75 MW installed, 1972); and a theoretical calculation of the total Japanese geothermal energy potential is in excess of 8,000 MW.

More complete estimates depend upon more detailed studies of geothermal systems throughout the world. Upward revision of estimate may occur if present day efforts are successful in utilizing lower enthalpy fluids in power generation. These efforts center around heat exchange between water and such working fluids as Freon and butane [113].

In general, the use of the geothermal fluid depends on the enthalpy and physical state. High enthalpy fluids (above about 200 cal/g) are useful in generating electricity. Lower enthalpy fluids are used as process heat in many industries. Both types of fluid may find application in desalination. Finally, low enthalpy fluids find use in space heating and in agriculture. Certain mineralized fluids may yield industrially valuable chemicals. Future development will be increasingly multipurpose.

Utilization of lower enthalpy fluids has progressed rapidly in Hungary (space heating), Iceland (space heating, agriculture, and industrial processing), Japan (space heating and industrial processing), New Zealand (industrial processing and agriculture), and the Soviet Union (space heating, industrial processing, and agriculture). Some application has been made in the United States. In Mexico and Kenya fresh water has been condensed from steam on a limited basis. Several countries of eastern Europe are planning to utilize hot water for space heating and agriculture. Multipurpose projects (electricity, desalination, perhaps minerals) are also planned for Chile and the Imperial Valley of the United States [10].

Additional information on diverse use of geothermal sources will be outlined on a broder scale in Chapter II-B.

A. Generation of Electric Power

1. Development status

Geothermal electric power is viewed by geothermal experts as a possible rival to hydroelectric power and, in the long run, even nuclear power. The volume of water needed for the cooling of a conventional thermal power plant is becoming an important factor in the construction of new plants. Fossil fuel plants waste about two-thirds of the heat contained in steam and nuclear plants, about 75 percent. The volume of water needed for these plants in the United States by 1980 has been estimated at one-sixth of its surface drainage runoff. Geothermal plants, on the other hand, do not require external sources of cooling water except for the initial charging of the system. Geothermal electric power is very profitable in regions where neither fossil fuels nor hydroelectric resources are available. Even if they are available, geothermal electric power offers considerable savings because there is no fuel cost, and capital investment and maintenance are considerably lower, when compared with conventional power plants of the same capacity. It is estimated that the cost of geothermal power ranges between 3.2 and 4.9 mills per kWh for dry steam fields and amounts to about 60 percent of the cost of electric power obtained from fossil fuel. The costs in fields producing a mixture of steam and water may be higher, but they are still competitive with conventional power plants [35].

The countries that have successfully developed geothermal electricity to date are among the wealthiest and most industrially developed in the world, such as the United States, Italy, Japan, the Soviet Union, New Zealand, and Iceland. However, the majority of countries in which exploration is under way, and where opportunities for future development are promising, are generally among the least developed of nations, lacking

the economic and technological base. But even with most highly developed countries there are regions that are lacking in energy resources, low in population, or remote from the industrialized heartland, where costs of electric power are often higher. Examples are Hokkaido, the northern island of Japan, the Kamchatka Peninsula of the Soviet Union, and parts of the Great Basin of the United States, all of which exhibit geothermal potential.

Many of the industrialized nations such as Italy, Japan and until very recently, New Zealand are poor in reserves of fossil fuels. In Japan, 75 percent of all energy is imported, and this figure is expected to increase over the next 10 years to over 85 percent. In New Zealand, where geothermal exploration has been under way since the end of World War II, recent discoveries of sizable reserves of natural gas have brought the development of geothermal electric plants to a halt. However, the Government of New Zealand will continue to encourage the direct use of geothermal energy in industry, agriculture, and space heating.

In general, we can expect increase use of geothermal energy, certainly in direct utilization. Despite certain disadvantages, such as inability to sustain transport over long distances, restriction to base load power application, relatively low efficiency and transmission losses and doubling of demand for electricity throughout the world, there is great need for development of geothermal energy. Especially in countries plagued by a shortage of fossil fuel reserves or an unfavorable balance of payments, there is an incentive to develop indigenous energy sources.

The first experimental generation of electricity from natural steam was undertaken at Larderello in 1904. In 1913 a 250 kw generating station came into service, marking the beginning of continuous generation of geothermal electricity.

After World War I, the concept of geothermal energy was carried to the rest of the world. Experimental borings at Beppu, Japan, began in

1919, and in 1924 a 1 KW generator was installed and operated experimentally. In the United States, test borings were conducted at The Geysers and Niland, California, in the 1920's. Although low pressure steam was found in abundance, the projects were abandoned for lack of a market for electricity. Holes were drilled at other fumarole areas in the United States in the 20's and early 30's, most notably in Yellowstone National Park. A test hole was drilled in Java in 1928, but no development followed.

In Iceland, the exploration of hot water aquifers by drilling began in 1928 at Reykjavik and in 1933 at Reykir, a few kilometers to the east Hot water from these systems was distributed to consumers by the Reykjavik Municipal District Heating Service. Before 1940, hot water wells had been drilled for heating purposes at Rotorua, New Zealand. In that year a great many wells were drilled for domestic use in Rotorua and in towns south of Lake Taupe.

World War II disrupted traditional patterns of living. In the reconstruction of war-devastated economics, attention focused again on geothermal energy. This was especially true in Italy, Japan, and New Zealand; all three were short of fossil fuels for power generation, and generation and transmission facilities had been largely destroyed in Italy and Japan [10].

More recently, geothermal power production has been taken up in New Zealand, Iceland, Japan, U.S., and USSR. Geothermal power plants in New Zealand already have a capacity of about 200 MW. Moreover, important geothermal exploration and drilling are now taking place in Chile, El Salvador, and Turkey. There is a growing interest in this natural source of energy, and many more countries are expected to take up large scale exploration work in the near future [25].

Present conditions. Presently the worldwide capacity of geothermal power plants is over about 1,200 MW.

Geothermal power stations are operating in a number of countries with various outputs. Most of these stations were not originally designed for their present size but were evolved in a number of steps as confidence gradually grew in engineering technology and in the volume of the geothermal reservoir exploited. For example, in New Zealand, the first stage was to build a 69 MW station which was later increased to 102 MW, followed by a second station of 90 MW tapping the same hot water aquifer. Of more recent years, other small projects have been completed, such as the 20 MW Matsukawa and 11 MW Otake stations in Japan using steam from 4 to 6 boreholes respectively. In many countries, there are current prospecting programs and drillholes which have been completed in places as wide apart as Turkey, the Philippines, El Salvador and Iceland to mention only a few. In New Zealand, a number of promising areas have been drilled such as Tauhara, Waiotapu and Reporoa which for various reasons are not being presently considered for power development (such reasons include estimates of the reservoir size, chemical deposition within the pipes, and the ratio of good to nonproductive holes). A particularly important factor of these boreholes is that they discharge steam-water mixture instead of steam only. Up to the present time, there is not a large scale attempt to use these waters except in the case of Iceland where large quantities are used in domestic heating [109].

Future trend. Forecasts for future development are difficult, because of growing environmental concerns, threatened shortage of conventional fuels, and legal and financial complications. Development should more than double present capacity by 1980. Sizable increases in geothermal facilities are to be expected in the United States, Japan, and the Soviet Union. However, the geothermal percentage of the total power system will remain small. Several underdeveloped nations most probably will construct small geothermal power plants, fitted to the scale of their national economics. These plants may represent a sizable fraction of those nations' electricity for 1980 [113].

Some estimates for potential development of geothermal energy by 1980 are:

At Larderello and Monte Amiata, Italy, increases in power generation are likely to depend upon conversion from noncondensing turbines. This may increase capacity by 15 percent over the decade. If significant discoveries of steam are made at Travale, Roccastrada, or Radicofani, there is likely to be new construction in the steam fields of Tuscany. If exploration elsewhere in Italy is successful, new generating facilities could be on line by 1980.

There are no plans to construct additional geothermal power plants in New Zealand in this decade. Industrial and municipal applications will be encouraged, however, and some generation of electricity may incidentally result in direct utilization of heat for industrial processes.

Plans have been made to increase generating capacity at The Geysers by 110,000 kw per year through 1975, at which time 630,000 kw will have been installed, making this the largest developed field in the world. By 1980, installed generating capacity might be about 1,180,000 kw, if development continues to be successful. In the Imperial Valley it is likely that pilot electric-generation and desalination plants will be operating by 1980. Capacity is likely to be between 10 and 20 MW for demonstration plants. By then also, one or more small-scale, closed-system, heat--exchanging electric generators may be installed in that region. Conceivably, a few other pilot stations may be operating, or full scale plants may be under construction, elsewhere in the western United States by 1980.

Several Japanese fields are likely to be developed in this decade. Matsukawa and Otake are scheduled for enlargement to perhaps 60 MW each. This would include some development at Takinokami near Matsukawa and some at Hachobaru near Otake. Questions of scaling, well life, and water disposal may delay development somewhat. Onikobe, Hachimantai, and Nasu, on Honshu, Shikabe and Hokkaido islands, are also potential sites

for power generation development; total installed capacity at these fields is not likely to exceed 30 MW by 1980.

The plant at Pauzhetka, in Kamchatka, USSR, may be expanded to as much as 25 MW by 1980. Other fields in the Kurile Islands or on Kamchatka may be put into production, probably in the range of 10 to 20 MW each. Space heating can be expected to increase greatly in the Caucasus and in regions of western and southern Siberia through the decade, so that by 1980 the consumption of hot water may surpass two million tons of fuel oil per year.

Similar increases in consumption of hot water can be expected in Iceland, with an equivalent of over one-third million tons of fuel oil used annually. Electric power generation may increase slightly at Namafjall, and may begin at Hveragerdi in the Hengil area. Perhaps 15 to 35 MW capacity will be installed by 1980.

In Hungary the consumption of hot water for space heating may more than double through the rest of this decade. Hot water heating schemes may become operational in Yugoslavia, Czechoslovakia, France, and elsewhere in Europe by 1980.

A second 75 MW plant may be installed at Cerro Prieto, Mexico, by 1980. Construction of generating facilities may be under way elsewhere in the central part of Mexico by that time.

At Ahuachapan, El Salvador, a second 30 MW facility may be in operation by 1980.

Small plants are likely to be operating or under construction in the Philippines, Kenya, Chile, Turkey, and Taiwan by 1980, and perhaps in Guadeloupe, Nicaragua, and elsewhere. Their aggregated output is estimated to be between 70 and 150 MW. Because of the 4 or 5 year minimum lead time required for exploration and construction, it is unlikely that extensive

plant construction will have been undertaken elsewhere by 1980. Conceivably, another 50 MW of generating facilities will be erected in Indonesia, Ethiopia, or China.

In general, conservative projection of worldwide geothermal generating capacity by 1980 is estimated at 2,500 MW. World consumption of electricity during that period is about to double, and the geothermal power component of world output will remain at less than one percent of total generating capacity. Direct utilization of geothermal energy is expected to increase at a faster rate, especially in eastern Europe (industry, agriculture and space heating).

However, more rapid developmentis foreseen in the 1980's. It will depend in part upon improvements in geothermal drilling and utilization of technology, increased knowledge of geothermal systems, and greater availability of funds for geothermal exploration and development [10].

There can be no doubt that, with techniques being improved from day to day, the production of geothermal energy will become more economical in comparison with other conventional and non-conventional sources of energy. It is thus essential to devote technique, practice and science to the knowledge that will make it possible to discover new geothermal fields and increase their utilization [14].

2. Technological aspects

One or more of several potentially important breakthroughs in utilization technology may greatly expand the development of geothermal systems, hopefully in the immediate future. The most significant of the possible breakthroughs are:

- Heat exchange technology that would permit utilizing heat from fluids down to $100^{\circ}C$ or less, since total heat contained in easily recoverable natural fields at temperatures of 100° to $180^{\circ}C$ is far greater,

perhaps by a multiple of 100, than total, easily available heat above 180°C;

- Multipurpose developments, including desalination and/or chemical recovery, that would yield significant sharing of total costs;

- Low cost mechanical, chemical, or nuclear fracturing of hot dry rocks to increase permeability, thus permitting introduction of fluids and recovery of stored energy;

- New methods for drilling low-cost boreholes to greater depth;

- New technology or other developments that favor wide applications to space heating, horticulture, and product processing; and

- Solution or control of all geothermal-resource problems at no greater cost than for corresponding environmental and other problems of competing sources of power.

Some of these technological breakthroughs could have profound effects on the recovering of geothermal energy from very large, gradient-dominated volumes of rock, such as the deep sedimentary basins and hot, dry crystalline rocks, which are unlikely to be utilized within present prices and technology [17].

In various geothermal fields, the possibilities of lasting output of electric power differ considerably. The most important variables to be taken into consideration are pressure, temperature, and noncondensable gas content. Technological improvements in geothermal power plants first require optimization of these conditions in the available fluid, since a decrease in pressure and temperature means a diminution in available adiabatic drop. An increase in noncondensable gas content means a rise in the energy to be spent in order to eliminate these gases. Regarding

improvements, we must use specific quantities, so we will refer to specific heat consumption since this is the actual entity that is provided for standards concerning steam turbines. To consider the plant as a whole and then give proper consideration to auxiliary units, we do not refer to heat consumption per power unit generated by the turbine alternator, but to heat consumption per net power unit, i.e., per power unit made available by the geothermal power plant [116].

Another utilization question is the choice of technology best suited to each type of geothermal resource. For the vapor-dominated systems and the high temperature, (above 200°C) liquid-dominated systems, such as that at The Geysers field, the steam is available at the wellhead. After filtering, it is fed to relatively low-pressure turbines that drive generators. In the higher temperature, liquid-dominated systems, the liquid in the reservoir flashes into a mixture of steam and liquid upon reduction of pressure by the well. After the liquid is separated from the steam, the steam is fed to a turbine. It appears that there is no pronounced need for research in these two cases. If it proves feasible to recover the thermal energy from hot, dry rock systems, the same may be said if the temperature of the formation is high enough to sufficiently heat introduced fluids.

However, in all cases it would be helpful to know more about gas content, particulate removal, noise control, removal of dissolved salts such as silica and boron, and disposal of brine, condensates, and solids.

It is believed that there are many geothermal reservoirs (perhaps as many as 80 percent of all reservoirs) in which the temperature is not high enough to provide fluids that may be used with existing technology to produce economic power. Successful demonstration that these marginal reservoirs can be economically utilized for generating electric power and other uses, such as commercial recovery of chemicals, would greatly expand the recoverable geothermal resources. For the generation of power from

such reservoirs, technology has made some progress in developing vapor-turbines (binary-fluid) systems in which heat is transferred to a low-boiling point fluid (such as Freon and isobutane), which is then used as the working fluid in a closed cycle system. Further technical research on a variety of such systems, as well as other power cycles deriving energy from hot concentrated brines, is needed. Desalination pilot plants using geothermal energy are needed, and mineral extraction may also require pilot plants [6].

Other technology for using hot water is rapidly developing, particularly with the use of heat exchangers. Rather than use the steam flashed from hot water directly, technology such as the Magmamax process (Magma Power Co., Los Angeles) and the Van Huisen Downhole Heat Exchanger (Geo-Energy System, Inc. Los Angeles) use binary systems to extract the heat without pumping up the water. The Magmamax process, for example, uses a heat exchanger to flash isobutane. The isobutane vapor then drives the turbine, is condensed, and returned to the system. The Downhole Heat Exchanger use clean water pumped through a closed system, which is converted to steam and collected in a reservoir. The steam is conveyed to power turbine generators with increased pressure and volume needed for required power output. Using the hot brine indirectly has two distinct advantages. First, since no brine is removed, the reservoir is left intact to continue gathering heat from the earth's core. Second, corrosion control and pollution abatement should be easier tasks since contaminated water is not brought to the surface [117].

In addition, binary-cycle geothermal power plants may benefit from the use of liquid fluidized-bed heat exchangers. A demonstration facility to test the geothermal application has been proposed and is in the testing stage by Allied Chemical Corporation. Their heat exchanger consists of a number of stages containing beds of particles fluidized by the hot geothermal water. Within each bed is a heat exchanger tube bundle through which the secondary working fluid passes. These stages are arranged so that the flow of secondary fluid within the tubes is counter to the flow of hot geothermal water used to fluidize the bed of particles. The recovery of heat from the geothermal water can be as high as desired, depending upon the

number of counter-current stages used.

The concept is based on earlier measurements in Allied Chemical laboratory on the heat transfer rates during crystallization of aluminum nitrate in a fluidized bed. This work showed that the salt crystallized is only on the particles in the cold stage and not on the walls or heat exchanger surfaces submerged in the bed. The temperature drop of the geothermal water as it passes through each stage causes some of the dissolved salts to precipitate out of solution. Two things tend to keep the tube surfaces clean:

- the large and cool surface area of the particles in the bed for the dissolved materials to precipitate upon, and

- the constant motion around the heat exchanger tubes of the particles in the bed.

The fluidized bed has advantages in the control of silica scale from high-temperature, water-phase geothermal wells. The bed particles are continuously agitated and have a scouring action on the heat exchanger tubes and wall surfaces. Silica scale forms on the bed particles (usually 0.2 to 0.3 mm quartz sand) and does not affect the heat exchange properties. Large tubes (up to 2 m diameter) can be used for the geothermal fluid to allow high volume flow and more reduction of scaling. Fluidized-bed heat exchangers have a heat transfer coeficient up to 2.5 times that for an exchanger without the fluidized-bed. A mixed flow of steam and hot water is not expected to reduce the exchange of heat [118].

a. Power plants and equipment

The generation of geothermal electric power in recent years has shown quantitative progress, rather than spectacular advances in new techniques. Several design refinements in turbines, condensers, and rotary exhausters, together with automatic or semi-automatic operation, have brought considerable improvement in overall plant efficiency. In order to obtain some useful energy at an early stage of well development, present

practice calls for the use of a small portable turbogenerator unit (not over 1000 kw capacity), which is quickly coupled to the first producing well and supplies electric power for immediate local use. Upon the installation of a permeanent unit, the portable unit is then removed for subsequent use elsewhere.

The manufacturing of geothermal generating components presents no special engineering difficulties and plant reliability has generally been very high for an average 90 to 98% load factor [35]. Any qualified manufacturer of conventional power plants can build a geothermal plant as a nearly routine operation. The competition between the manufacturers is mainly in cost and delivery time.

In the present state-of-the-art, it is likely that the routine power generator will be a 55 MW machine for a large operation, possibly with two generators in the same building, as in The Geysers. The size of the generators is a critical factor for the profitability of a geothermal venture. Some of the main factors involved are: the steam capacity of the geothermal field, the output and the spacing of the wells, the power demand, and the delay time.

A geothermal power unit consists of three elements: the steam producing area and wells, the steam pipeline system, and the power plant. These three elements are interrelated and the cost of the project should be studied taking all of them into consideration. The choice of the power plant size is the most difficult decision for the geothermal programmer. The plant capital cost per kW decreases when its size increases. However, a large plant requires more supplying wells and an increase in expenses for the steam pipelines. There is an obvious relation between the spacing of the wells, the pipeline length and the optimum size of the geothermal power plant unit. The present trend of development is by stages of 50-60 MW in the large fields and of 10-20 MW in the less producing fields.

In the present state-of-the-art, it seems appropriate at 50-60 MW to limit the size of a single generator operating by dry steam. The size of a concession or a leasing project should be large enough to provide the fuel for at least one such generator. In an undrilled area, the size of a concession should be over ten thousand hectares. One thousand hectares seems to be the minimum size in the areas close to the proven areas [127].

In this chapter various components of a geothermal plant will not be described in detail. Some major characteristics, changes, innovations and improvements in design will be outlined for comparative study only.

There are several cycles of exploitation of steam that can be adopted, such as:

Noncondensing or direct cycle with atmospheric discharge turbine. Its specific consumption is approximately 20 kilos of steam per kWh, which means 80 tons/h for 4000 kW (pressure: 5.5 kg/cm^2 abs, and temperature of 200^{o}C). Several similar units can be installed where large quantities of steam are available [110]. They could also be fed with secondary steam or with flash steam, but in both cases a condensing cycle would be advantageous. This type of turbine is the simplest possible and least expensive in capital and operating cost. It occupies the smallest building space, requires the minimum amount of auxiliary equipment, and is more readily adaptable as a portable unit. Since the steam consumption may be twice as much, or even more, for a condensing plant, the cost of steam delivered to the turbine inlet is a significant factor in the total cost of operation. Comparatively high steam consumption is the main disadvantage.

The noncondensing turbine-generator units range in size from 500 to 6000 kw. Outside this range, smaller units would be of little interest, as internal combustion engines would be more suitable, while

larger ones would require great quantities of steam which, if available, could be better utilized in condensing turbines. Of particular interest is the design of these units, which permits their transportation and erection as complete units, without heavy lifting equipment. The heaviest lifting necessary at site is that requiring lifting the rotors for maintenance purposes. They may even be installed outdoors and can be operated by remote control [107].

This utilization cycle, being the simplest is also the least expensive. It is the type most advantageous for underdeveloped countries and the most advisable in any new area of exploitation [110].

Fig. 18 is a schematic diagram of a condensation cycle with direct steam outlet.

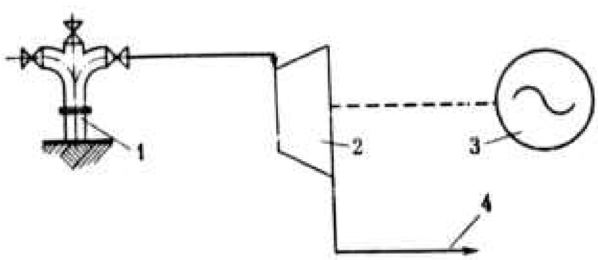


Fig. 18. Schematic diagram of a condensation cycle with direct steam outlet [40].

1- Wellhead; 2- turbine; 3- generator; 4- outlet to atmosphere or chemical plant.

A condensing steam turbine cycle with heat exchanger, in which the steam exhaust gives into a vacuum which is created by condensing the steam in a condenser just after it leaves the turbine. A large quantity of cold water is supplied to the condenser and condenses the steam either by mixing with it in the form of a spray (as in jet condensers), or by cooling tube surfaces on which the steam condenses (as in surface condensers).

With condensing turbines, several auxiliary equipment are required such as condensers, gas exhausters, circulating water pumps, and cooling towers or other cooling arrangement.

A condensing turbine will produce more power from the same quantity of steam than a noncondensing turbine, particularly when inlet pressures are fairly low. The power output also depends on the degree of vacuum attained in the condenser, amount of noncondensable gas in the exhaust steam, and the capacity of the gas exhausters. It can be said that for turbine inlet pressure likely to be of interest (less than 100 psi abs.), a condensing turbine will produce at least twice as much power as a noncondensing turbine [107].

In this type of installation, the natural steam runs through a heat exchanger, thus generating the secondary steam to feed the turbine. The steam exhaust is discharged into a condenser under vacuum. The advantages of this cycle are the following:

- it can be used with very dirty and incrusting steam;

- it allows the total utilization of the chemicals contained in the steam.

With a steam containing 10-15% by weight of noncondensable gases, its thermal efficiency equals that of a direct inlet cycle and it can be even more efficient than the direct cycle.

The installation cost is equal to or slightly higher than that of an analogous installation working with a direct condensation cycyle.

Below is a schematic diagram (Fig. 19) of a condensing steam turbine cycle with heat exchanger.

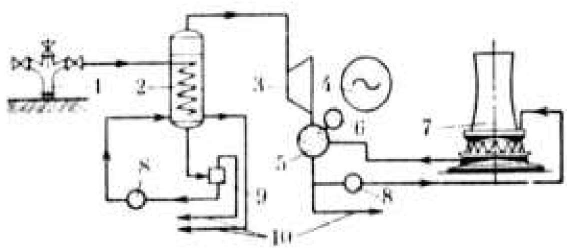


Fig. 19. Condensing steam turbine cycle with heat exchanger [40].

1- Wellhead; 2- heat exchanger; 3- turbine; 4- generator; 5- condenser; 6- vacuum pump; 7- cooling tower; 8- pump; 9- degasification equipment; 10- outlets.

Condensation cycle with direct steam inlet. In this cycle the natural steam is fed directly into the turbine and afterwards to the condenser [110]. Mixture of cool water and condensate, already used in the turbine, is discharged from condenser into the tank and hence by circulating pump into the cooling tower. From the cooling tower, cold water is fed back into the condenser [40].

Gases contained in the steam are removed from the condensers with special gas extractor compressors to maintain the vacuum.

The condensation cycle is the most modern plant cycle, and was adopted in all power plants constructed by the Larderello Company during the past 20 years [110].

Fig. 20 is a schematic diagram of a condensation cycle with direct steam inlet.

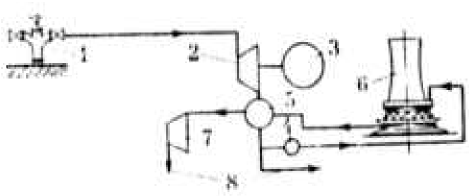


Fig. 20. Condensation cycle with direct steam inlet [40].

1 - Wellhead; 2 - turbine; 3 - generator; 4 - pump; 5 - condenser; 6 - cooling tower; 7 - gas extractor compressor; 8 - outlets.

Regardless of which type of cycle is selected, the plant for generating electric energy must be located near the steam wells because of the low steam pressure. The distance from the wells is determined by the size of the units which dictates the number of wells required, and suitable foundation conditions. Because a great quantity of steam is obtained from the wellhead when the pressure is lower, it is not advantageous to use up the pressure by having too long a pipeline. The pressure drop can be reduced by increasing the pipe size. However, this also increases the cost of the pipe and the heat loss from the pipe [121].

The following are briefs on some components of a geothermal power plant:

Condensers in geothermal plants have been of the jet (spray) type in which direct contact is made between the condensing steam and the water. Originally jet condensers were built as cylindrical shapes and suspended beneath the turbine. Later models evolved into more nearly rectangular form. They were still squeezed into the confined space between the massive concrete columns supporting the turbine deck. An alternative idea derived from nuclear power stations is to build the jet condenser into a shape where it can serve as a structure to carry the turbine. In this case

the vapor (gas) cooler which is used to reduce the volume of the mixture sucked off by the air pump, is best incorporated in the main body.

The natural place for the condenser is immediately below the turbine and the simplest way of providing for the discharge of the water from the vacuum space is a barometric leg required to be about 30 ft high. Schematic layout of such a plant is shown in Fig. 21.

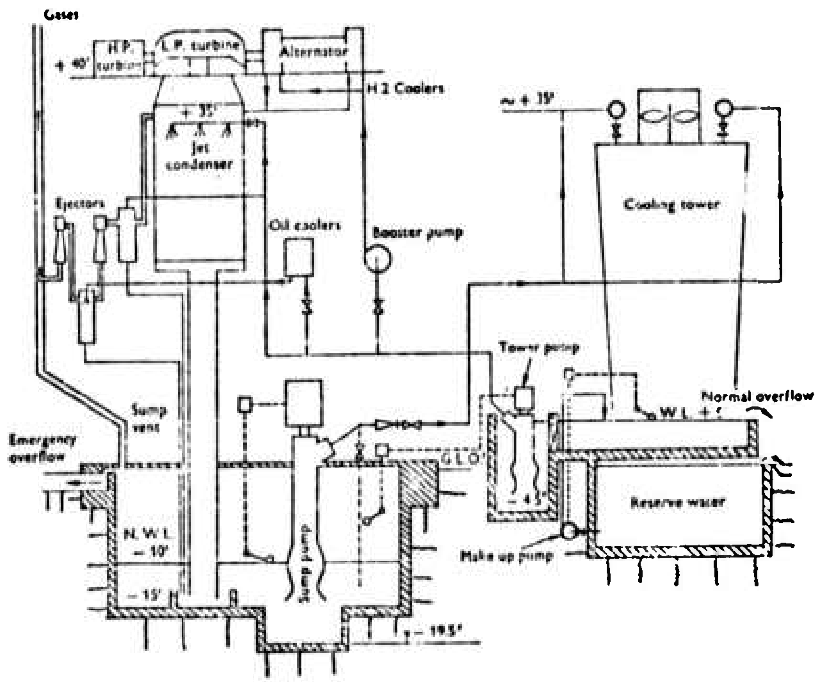


Fig. 21. Schematic diagram of a cooling water circuit with condenser [106].

It is to be noted that where cooling towers are used, two sets of pumps are required, one set to lift the water from the sump to the cooling tower, and another set to lift water from the cooling tower basin to the condenser. Maintenance of desired water levels in sumps and basins may call for automatic control. Occasionally the ground formation

may permit of the cooling tower being placed on such a level as to enable the water to be lifted by the vacuum into the condenser instead of being pumped [106].

The condenser in Cerro Prieto, Mexico, produced by the Tokyo Shibaura Electric Co., will be the world's largest in size and condensing capacity (Fig. 22).

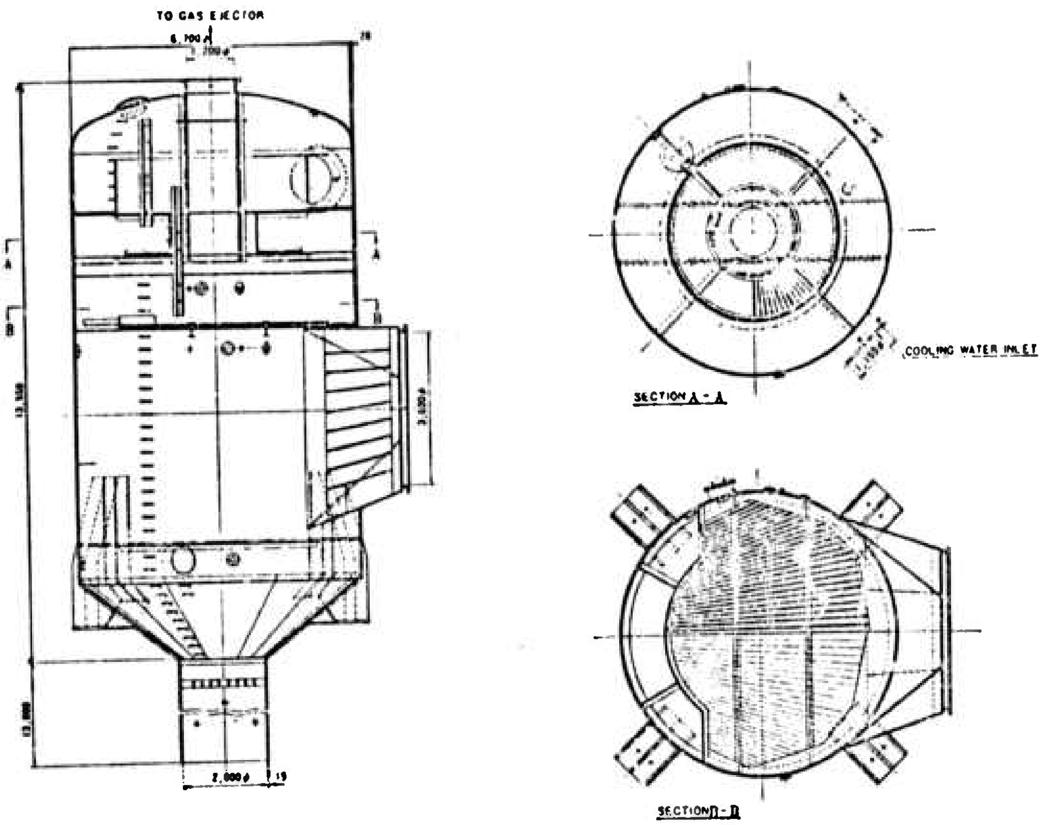


Fig. 22. Condenser assembly of Cerro Prieto, Mexico [122].

The condenser has a water spray shelf with numerous slits, and the steam flowing upward and condensing without passing through the cooling water curtain crosswise. The field test results indicate that

pressure loss was within the foreseen 5 mm Hg and the required condensing capacity was satisfied [122].

In general, the geothermal steam does not have to be condensed separately and returned to a boiler, and therefore the less expensive direct-contact condensers can be used. In some plants, barometric condensers are in use, allowing that the turbines can be installed at ground level and the circulating water pump suction is at atmospheric pressure. However, low-level, direct contact condensers can be mounted directly under the turbine exhaust and the cooling water can flow into the condenser by vacuum suction without pumping. No makeup water is required for the cooling tower evaporation because the steam condensate provides more than the requirement of the cooling tower, where about one-fifth of the condensate is left [114].

Jet condensers are generally used for the endogenous steam plants, because they are practical and of easy upkeep and cleaning, although they require extraction of the circulating water and condensate by means of a barometric pipe.

The adoption of normal surface condensers would have several problems concerning selection, use, and corrosive resistance of the materials, that would bring more delicate and expensive operation and maintenance of the plant.

One advantage of the normal surface condensers would be the absence of any barometric pipe because the condensate would be extracted by a centrifugal type extraction pipe [131].

Compressors. Some improvements were made in the construction of the compressors by building variable revolution compressors, increasing the size of gas intermediate coolers, and designing the compressors themselves for a suction pressure of about 0.07 ata. This is the most

suitable pressure in direct condensation steam plants for obtaining maximum operating efficiency at an average ambient temperature of 15°C [116].

More efficient than the water jet ejector is a centrifugal compressor, especially where the gas quantities to be handled justify its use. They have run successfully for many years at Larderello, Italy, in multicylinder form with spray intercooling with total ratio about 10:1. However, corrosion and erosion troubles have been absent despite the wet and corrosive gases [106].

Silencers. Where it is necessary to allow wells to discharge to the atmosphere for long periods, the noise created may be intolerable if some type of silencing device is not installed. Not only is the noise annoying to those working or living in the vicinity, but it can also cause permanent hearing damage in people continuously exposed close to its source.

There are special equipment and methods for silencing well discharge under different condtions. One method is to discharge the flow through a submerged outlet into a river or pond. This method achieves complete elimination of noise, but for environmental reasons is restricted in its application.

A second method is to allow the steam to gradually expand into a large diameter concrete pipe outlet laid horizontally, of gradually increasing size, with the end of one slightly projecting into the next one.

A third method is to provide twin towers for vertical escape of steam, combined with a basic structure into which the well discharge is conducted and water is separated by centrifugal action and separately discharged in a controlled manner [107].

Cooling towers. Cooling towers for geothermal stations are costly per kilowatt because of the much greater heat rejected per kWh. The water is pure condensate and can be concentrated to a high degree. Also, it might be supposed that the content of H_2S and CO_2 would render the water strongly acid, but it is not the case in practice as CO_2 is largely scrubbed out in cascading through the fill. The H_2S is partly retained and partly oxidized to SO_2+H_2SO_4 and S. Luckily geothermal steam usually contains traces of amonia which, being highly soluble in cold water, is retained and build up until it corrects the pH to the slightly alkaline side of neutrality. It combines with the HSO_4 to form ammonium sulphate and with the CO_2 to form ammonium bicarbonate. Some free sulphur is also produced which makes the water "milky".

Sulphate attack is likely to occur on concrete cooling towers unless sulphate resisting cement is used (or equivalent pozzolan added). Where gases collect in cooling towers a resistant coating may be necessary.

Cooling water. Required quantity of circulating water is arrived at by a rough rule that the latent heat of the steam at the condenser is on the order of 1,000 BTU/lb. Hence every pound of steam to be condensed requires 50 pounds of water with a temperature rise in the condenser of 20°F. The fact that the steam will be wet at the exhaust is not important since the heat content above vacuum temperature of the water accompanying the steam is negligible. Where a more accurate calculating of cooling water requirement is called for it is necessary to know the heat consumption of the turbine. While a source of natural cooling water is advantageous for geothermal stations, a geothermal plant is unique in providing its own make-up for cooling towers automatically [106].

b. Air - gas extraction

In conventional steam plant the amount of gas in the boiler steam is negligible. The air extraction plant is primarily designed to extract air which has leaked in through flanges, shaft seals or possibly through

packings at the condenser tubes. In geothermal plant the steam rarely contains less than 1/3% of incondensible gases by weight and may contain as much as 4 percent. The air leakage may well be about the same proportion as conventional plant, but the circulating water also beings in a large quota of air in solutions commonly taken to be 3% by volume equivalent to 34 ppm in cold water. With a 50 times ratio of water to steam even this small amount of dissolved air in the circulating water implies 0.17% of steam flow. Hence, it is readily seen that the air or gas extraction plant must be much larger with the geothermal plant using jet condensers than in conventional plants. Moreover, the gas pumped out is a mixture of air, CO_2, and H_2S. This is a highly corrosive combination entailing rubber linings, fiber glass, or stainless steel piping if periodic patching or replacement of mild steel is not acceptable. Luckily some of the gases are entrained in the water going down the barometric tube.

Regarding the type of air extraction plant, the most favorable method for many years in conventional plants was the steam jet ejector. This replaced, in about 1906, the reciprocating air pump which was improved by using a steam jet in the form of a Parsons vacuum augmenter enabling it to reach a higher vacuum. When the steam jet ejector took over it was claimed to be efficient because the heat in the jet steam was recoverd by warming the condensate. Actually this claim was spurious because by 1906 feed heating by bled steam had already been introduced and thereafter only a small credit could be given to the heat recovered from the jet ejectors. However, they have remained in use even though their efficiency rate is very poor, not better than 5%. Large size may be noisy. A better efficiency is obtained in conventional plants, by using water jet ejectors which, though they work on the same momentum principle, do not entail the same rejection of latent heat. However they require large amounts of water for geothermal duty and cost more than steam jets.

Consideration also has to be given to the means of discharging the gases to the atmosphere. H_2S and CO_2 are heavier than air. Accordingly it may be necessary to override considerations of efficiency and to use steam

ejectors since the hot steam from the second stage provides levitation to carry the gases away from the top of the vent pipe. A natural draught cooling tower forms a convenient chimney to ensure that the gases can be discharged at sufficient height.

Experience shows that safety precautions such as avoiding unventilated pits and dealing adequately with miscellaneous drains carrying gases, are advisable from human safety and comfort aspects. They also help to avoid failures of minor electrical equipment such as instruments and relays where fine copper or resistance wires are readily attacked by traces of H_2S. An outdoor plant is less troublesome in these respects than a normal power house.

It is worth mentioning that the most severe corrosion damage to geothermal steam turbines occurred during periods when they were standing still. This is because valves are rarely steam tight and a small amount of steam leaking into a turbine in the presence of air will do severe damage as the gases are concentrated in the condensate and water line attack results. Hence when geothermal plant is not in operation precautions must be taken to ensure tight steam shut off by provision of two valves in series with a vent to atmosphere between, and preferably also by drying out the turbines with hot air after shut down [106].

Extracting gas to maintain a vacuum only causes leakage in conventional plant equipment. However, the geothermal plant has the remarkable characteristic that the gas quantity is approximately 100 times greater than in conventional plants and may change with the blowing condition of each well. Extraction is carried out with a mechanical pump and a steam ejector. The steam ejector is a simple construction which can prevent corrosion and ease operation. However, operating steam pressure limits efficiency [122].

In general, a wide variety of means in evident for the extraction of the noncondensable gases from the plant condensers, ranging from steam ejectors, water ejectors, rotary exhausters to reciprocating pumps. The means adopted must surely be dependent upon the available steam pressure for ejectors and also upon the gas content of the steam. Each case must be judged on its merits.

However, no attempt appears to have been made to use waste pressurized hot water for operating ejectors. This would seem to offer a promising field for investigation for wet geothermal fields [128].

c. Alternative fluids

Most geothermal power stations using water/steam fluids operate on the principle of passing the separated well steam through the high pressure stage of the turbine, then flashing the separated hot water for turbine use in a low pressure stage. The remaining hot water is usually discarded for waste unless a convenient consumer of low grade heat can be found.

As a means of overcoming this waste, considerable interest is being shown in the possibilities of utilizing low temperature secondary fluid systems incorporating liquids with low boiling points. Under such an arrangement, the primary geotherm liquid is passed through a suitable heat exchanger, where it vaproizes the secondary fluid i.e., alternative fluid which then passes as a vapor to an appropriate turbine for the production of power. Having completed its usefullness in the turbine the vapor is condensed to liquid and returned to the heat exchanger to continuously repeat the process.

The main advantage arising from the use of a secondary system (Freon, butane, etc.) is that more power can be obtained from a given geothermal steam/water mixture. Apart from the technical advantages which it offers in the exploitation of two phase wells, the use of a secondary system allows power to be produced in fields where only hot water can be obtained at temperatures so low that a steam cycle is uneconomic.

Work with secondary systems has been carried out in the USSR, at the Panzhetka geothermal power station using Freon 12. Compared with conventional steam system, it was found that both systems were approximately equal economically, although the employment of Freon involved a larger and more complicated installation with more difficult maintenance problems. Despite this, the secondary low temperature cycles offer considerable promise for the future, although it may be necessary to find cheaper and more suitable fluids. In this respect, it has been reported that a secondary cycle, geothermal power station will be built in Nevada using isobutane as the working fluid [129]. In addition, a 300 kW plant on the island of Ischia, Italy, in 1943 used ethyl chloride as secondary fluid, and hot water at 95°C.

The refrigerant have a higher vapor pressure and thus the turbine is more compact by virtue of the higher density. Risk of corrosion in the turbine is also avoided as is wetness loss with some refrigerants. Corrosion risk is of course transferred to the heat exchanger and to the condenser which has to be of the surface type [106].

However, no attempt has been made to optimize the Freon cycle. One reason is that data in the supercritical pressure region, and in the moisture region, are lacking. The characteristic of Freon is to superheat on expansion so that vapors at the turbine exhaust contain approximately 50°F superheat. This exhaust superheat represents a cycle loss that might be recoverable by reboiling some of the condensate to produce low pressure vapors which would then be readmitted to the turbine. This additional complication is not considered advisable, but it does suggest that some other operating conditions or fluids might be found which will avoid this loss and give even better cycle efficiency.

A turbine designed for operation on Freon appears to be technically feasible. It would obviously have a higher manufacturing cost than a steam turbine of the same rating. The Freon turbine would be much

unlike a steam turbine, and the aerodynamic properties of Freon are so unfamiliar that it is obvious that considerable engineering study will be required to develop a satisfactory design [30].

A recent effort has been focused on using isobutane as the working fluid operable in a closed cycle. Geothermal fluids from wells vaporize and super heat isobutane in a heat exchanger. Isobutane vapor then expands through the turbine to generate power, and the exhaust vapor condenses in a water-cooled condenser before it enters the heat exchanger to complete the cycle [130].

As mentioned earlier, various fluids can be used in the power cycle, but isobutane was shown to be most economically favorable for developing power from water at about 325°F.

The cycle diagram (Fig. 23) shows how isobutane vapor, expanding through a turbine, yields its energy to drive a generator. This vapor turbine cycle has been developed by the Magma Energy, Inc. of Los Angeles and named the "Magmamax" is in testing stage. The turbine is a three-stage, radial-flow type, and will deliver approximately 9000 kW at the generator terminals depending on cycle conditions.

The vapor-turbine cycle using isobutane or other suitable fluids has many advantages over the flashed-steam or indirect steam heating cycles in the following:

- Water pumped from the reservoir at pressures above saturation reaches the surface at nearly maximum well temperature, whereas water lifted by steam suffers severe temperature losses.

- Since water at full pressure retains its gases in solution, the gases can be returned to the ground without danger of atmospheric pollution.

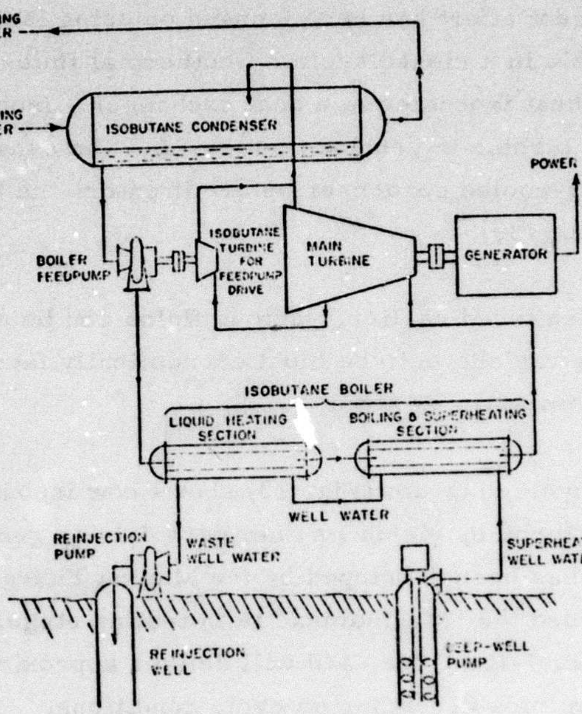


Fig. 23. Vapor-turbine cycle diagram [126].

• If steam and dissolved gases were permitted to escape from the water, the chemical composition of the water would change, very likely causing precipitation of solids out of solution, and plugging of wells.

• Keeping water at high pressure throughout the heat exchangers helps to minimize heat-exchanger tube stresses. The possibility of stress corrosion, which is often the chief cause of failure in high-temperature hot-water heat exchangers, is thereby reduced.

- Because the vapor turbine incorporates fewer stages, and because the vapor volume change through the turbine is not as great, the vapor turbine generally offers more efficiency than the steam turbine.

- Because wheel speed in vapor turbines is lower than that in steam turbines, design problems are simpler and blade stresses are much less severe.

- The vapor-turbine cycles can be relatively quiet; flashed-steam cycles require costly noise-abatement measures.

- Isobutane turbines operate above atmospheric pressure throughout the cycle. The possibility of air and oxygen getting into the turbine and causing corrosion or explosive mixtures is eliminated. Air entering the system under vacuum is a major cause of corrosion in steam systems.

- Isobutane and other such fluids are relatively simple and inexpensive.

- Isobutane turbines are much smaller and, therefore, less costly than steam turbines of the same power output.

- Isobutane remains dry throughout its expansion through the turbine, thus eliminating the erosion of blades by water droplets that is so common in steam turbines.

- Because isobutane is compatible with oil, internal bearings can be used in the turbine, yielding a turbine much more rugged and lower in cost, and requiring only a single shaft seal at the coupling end of the turbine, thus eliminating the long, complicated, leaking shaft seals required in a steam turbine.

- Since isobutane is noncorrosive, there should be no need for the expensive stainless steels often required in various parts of the turbine in the flashed-steam cycle.

- Because the condensed isobutane has lower density and lower latent heat than steam, cavitation damage should not occur in the boiler feedpump.

- Because corrosion problems are less severe, the isobutane boiler feedpump can be made from cheaper materials than a water feedpump.

- Because isobutane turbines have much lower rotating inertia than steam turbines of the same power, the short-circuit torque problem from the drive couplings is virtually eliminated.

- Because isobutane turbines can be designed to utilize lower condensing temperatures, cycle efficiencies are improved and water rates are reduced below those of steam turbines.

- With no air or noncondensable gas in the condensers, isobutane condensers can be made 100 percent effective; with steam condensers, gas in the system reduces condenser efficiency by increasing condensing pressure.

- Steam turbines can require substantial gas-removal equipment; isobutane turbines, none.

- The isobutane cycle permits efficient transfer of heat from well water down to quite low temperatures; water can be discharged from the generating plant at temperatures as low as 120°F. By contrast, steam cycles could rarely be economic at water-discharge temperatures below 212°F.

With the development of efficient vapor-turbine cycles better pumping equipment and heat exchangers, and more efficient cooling systems, we now feel confident that low cost power can be produced from many available sources of geothermal heat [126].

While the theory of the vapor turbine cycle is simple, many new ideas and improvements needed to be added to the basic cycle in order to make it practical and economically sound. All of the major problems are thought to be solved, and the new "Magmamax" power plant is believed to be not only a technical, but also an economic success. This can open the door to tap the limitless quantities of heat and produce a great amount of power. Best of all, this can be done without any pollution of atmosphere and water [120].

d. Selection of material

Initially common construction materials were adopted which were already used in other plants. The materials required at the wells (drill rods, casings, etc.) had already been evolved from a long experience of oil well drilling where sour wells containing sulphur were known to produce catastrophic failure in high strength alloys. Early experience showed severe cutting of valve seats and faces wherever leakage of wet steam took place. Many valves accepted in other industries were found to be incapable of making a tight seal or closing against the flow under pressure. Stelliting* of faces was the remedy along with use of stainless trim.

By the time large geothermal turbines started to be built, evolution of blade materials had already settled on 12% Cr-iron, i.e., low carbon as the best material and this (even with higher carbon) was found to

* Stellite - trade mark for any of various alloys composed essentially of 75 to 90 percent cobalt and 10 to 25 percent chromium with or without small amounts of other metals added and used esp. for cutting tools, hard wear-resistant surfaces, surgical instruments, and cutlery.

stand up to H_2S so long as it was not in a hardened (martensitic) state.

Before it became known that geothermal steam has generally similar properties in all of the fields, it was essential to carry out tests on samples of a wide range of materials both for general corrosion resistance and for stress corrosion cracking. Such tests required interpretation therefor it was possible to derive misleading ideas. For instance, the chemist removes the corrosion film and deduces the loss in weight. He thus exaggerates the corrosion rate in that the initial attach may well produce a protective film which would have greatly slowed down the subsequent rate of attack. This is the case with ferrous materials exposed to H_2S at least in the absence of oxygen. Similarly, the test samples are commonly chemically cleaned before exposure, which tends to exaggerate corrosion rate since quite small films of oil will confer some protection.

Short period tests are all that can be undertaken usefully in the few months available between the decision to go ahead with the project and the drawing up of the specification. Consequently, accelerated techniques must be adopted in order that data be obtained in a period of less than a year. The risk must be taken that an alloy which might have been just acceptable is given a bad reputation. In other directions of corrosion fatigue and erosion resistance, it is practically impossible to carry out proper mock-up tests on site. In wet conditions electrolytic corrosion as well as crevice corrosion between dissimilar metals, must be expected. Thus in the end the designer or specification writer has to cautionsly exercise judgment. The chemist or metallurgist often selects materials purely on general corrosion resistance and chooses the best. For selection of materials, price and corrosion resistance are not the only criteria and other properties must be considered. For example, austenitic stainless steels are particularly sensitive to stress corrosion cracking in the presence of chlorides. Moreover the following environments are to be considered; an alloy found by test unsuited to one may be valuable in another geothermal installation in the following cases:

- before separation where water and steam are both present and in possible rock particles,

- in steam pipes where initial contamination with salty bore water is gradually replaced by condensate,

- at the entry to the turbine where the steam is almost dry,

- at exhaust from the turbine where it is very wet, and impact erosion occurs,

- in the condenser where circulating water and air are present, gases may be concentrated and impact erosion may occur,

- in the gas extraction circuit where the most virulent mixtures of air, gas, water and vapor are found, and

- in the circulating water circuit where gases may be released and flashing water and gases are discharged from drains.

So far only few manufacturers have experience of geothermal turbines. Others have mainly shied away from the difficulties which their metallurgists, probably on the basis of hasty tests or judgment, tended to exaggerate. It appears that there is now a risk of a swing in the other direction with new manufacturers and ideas based on nuclear designs coming in with possibly erronous notions on corrosion based on misunderstanding of published data or an excess of confidence derived from insufficient background knowledge [106].

In general, equipment needed in a geothermal plant is quite simple and manufacturing of various generating components presents no special engineering difficulties. Plant reliability has been very high for an average 90 to 98 percent load factor. The design and construction of equipment are easier than for fuel plants, except for a problem of materials. In the case of geothermal steam, the quality of steam is very impure, i.e., the machines have to utilize directly or indirectly uncontrolled steam gushing from the earth. The foreign matter which appears as scale in equipment is soluble in steam, and geothermal steam blows out with gaseous impurities

including hydrogen sulfide which has a great influence upon corrosion. Thus, the accuracy of corrosion tests in selecting material is important as it will affect equipment life and power generating costs.

For example, before planning the equipment of Matsukawa geothermal plant, Japan, a corrosion test was carried out on 14 kinds of material in steam and in condensate water. Test points were dimension and weight that decrease rate, tension test and microscopic examination. By this test, materials were selected and allowable stresses and corrosion allowance were decided. Additional tests were carried out to decide the exact amount of corrosion and crack sensitivity by stess corrosion. Also, corrosion rate affected by steam velocity, temperature and wetness, corrosion crack sensitivity in the vicinity of the limit of stress and corrosion fatigue were examined. These tests showed that the corrosion of materials was caused by the sulfuric compound in the steam, and that the metals containing Ni and Cu were susceptible to this compound, and were affected more, but corrosion cracking was not found. The tests in condensate water were made by immersing test samples into a mixture of condensate from the surface type condenser and cooling water which have the same characteristics as water in the barometric condenser. It was determined that no metals had corrosion problems and epoxy resin coating was an excellent anticorrosive.

In spite of differences of steam composition of Matsukawa, Japan and Cerro Prieto, Mexico, the nature of the steams are almost similar to the influence of corrosion. It is true that the content of Cl which affects corrosion in Cerro Prieto is greater than in Matsukawa but it can be assumed that the fundamental design does not need to be changed.

The following table shows kind of materials used in equipment for the three plants (Matsukawa, Cerro Prieto, and The Geysers) and the final results of the corrosion test at Matsukawa geothermal plant [122].

Location	Material name ( ) in ASTM symbols	Corrosion rate 10^{-3} mm/yr
Turbine casings	Carbon steel plate (A283-6rD)	636
Infringment shield	Stainless steel plate (410)	21.3
Rotor	1% Cr, 1.25% Mo, 0.25% V, Forged steel	623
Buckets	Low carbon 12% Cr steel (410)	21.3
Nozzle diaphragms	Carbon steel plate (A283-6rD)	636
Nozzle partitions	12% Cr Al alloy steel	49.4
Labyrinth packing strips	15% Cr, 1.75% Mo steel	
Valve bodies	Carbon steel plate	636
Valve seats	Stellite welding	
Bearing babbits	White metal (D-23-6)	
Oil cooler tubes	Al	
Tube sheets	Naval brass sheets and plate (B-111)	4.92 in condensate
Water boxes	Cast iron (48-35)	
Condenser shell and tail pipe	Epoxy coated carbon steel	2.84 in condensate
Condenser tray	Stainless steel (304)	21.2 in condensate
Gas ejector	ditto	

B. Other Applications

Besides generating electric power, geothermal energy has broad application in several branches of the national economy. There are presently many engineering projects of varying scale, purposes, and stages of completion [31].

Geothermal resources are being considered for diverse exploitation and most possible uses, whether of low- or high-temperature appear to be economically viable with great advantages to domestic and industrial development [34].

In general, geothermal energy could be used for a great many heat-consuming processes, such as in the following incomplete list:

Sugar processing in conjunction with paper manufacture from begasse
Paper manufacturing from wood pulp
Total gasification of coal (Lurgi process)
Salt production
Powdered coffee production
Dried milk production
Cattle meal from Bermuda grass
Rice parboiling
Textiles
Fruit or juice canning or bottling
Other food processing, canning or crop drying
Plastics
Timber seasoning
Fish drying and fish meal production
Recovery and processing of certain minerals (e.g. diatomite)
Refrigeration
Air conditioning
Horticulture and raising of vegetables under glass
Heavy water production
Recovery of valuable trace elements from geothermal waters.

However, not many of these applications have been practically used, but greenhouse heating is extensively practiced in Iceland and the USSR, air conditioning is used in New Zealand and the USSR, there is a very large

paper manufactury in New Zealand, a diatomite recovery and processing plant has been established in Iceland, and plans have been drawn up for heavy water production in Iceland.

The actual production costs of these industries are of little significance, but the point of importance is that these production costs are in every case lower than could be achieved by alternative means [95].

In general, application of geothermal energy has both its problems and its rewards. Experience shows that the problems have a way of disappearing as research and development advances in any specific application. It is much more likely that each new project will involve many new aspects more or less specific to itself. Hence, any widespread use of geothermal energy is very different in research and process development. This is especially true of industrial applications, because the differences lie not only in geothermal and local conditions, but also in the reevaluation or redesign of a great many industrial processes.

The most striking characteristic of geothermal energy is its immense versatility. As a rule, its application in a major project will be governed by one or more specific objectives, but once it is introduced, certain other uses appear. Thus, the main objective may be some kind of evaporation, while the side uses may be drying, simple process heating refrigeration, space heating or even the production of electric power for the plant. Major industrial enterprises, and sometimes agricultural ones, may become, in effect, combined schemes for the application of geothermal energy.

The low cost of natural steam is in fact such a strong incentive that many new and more suitable processes may be established to take advantage of this, or older ones may be rearranged more or less completely. However, every such case has its own particular problems regarding raw materials, transportation, markets for the products and other circumstances, which must be thoroughly scrutinized before final recommendation.

In process heating, practically the whole range of geothermal fluid temperatures (both steam and water), may be used in one way or another. Specific applications often require definite temperatures, and either steam or water may be desirable [78].

However, there is increased interest in the use of low enthalpy geothermal sources for various purposes in many countries. Various combined schemes are receiving growing interest, and it is likely also that high enthalpy geothermal fluids will, due to their low cost, find increased industrial application besides the generation of electric power. The use of low boiling heat carriers seems to offer attractive possibilities toward improvement in the utilization of geothermal energy especially in power generation. Refrigeration with geothermal energy is a new and promising field.

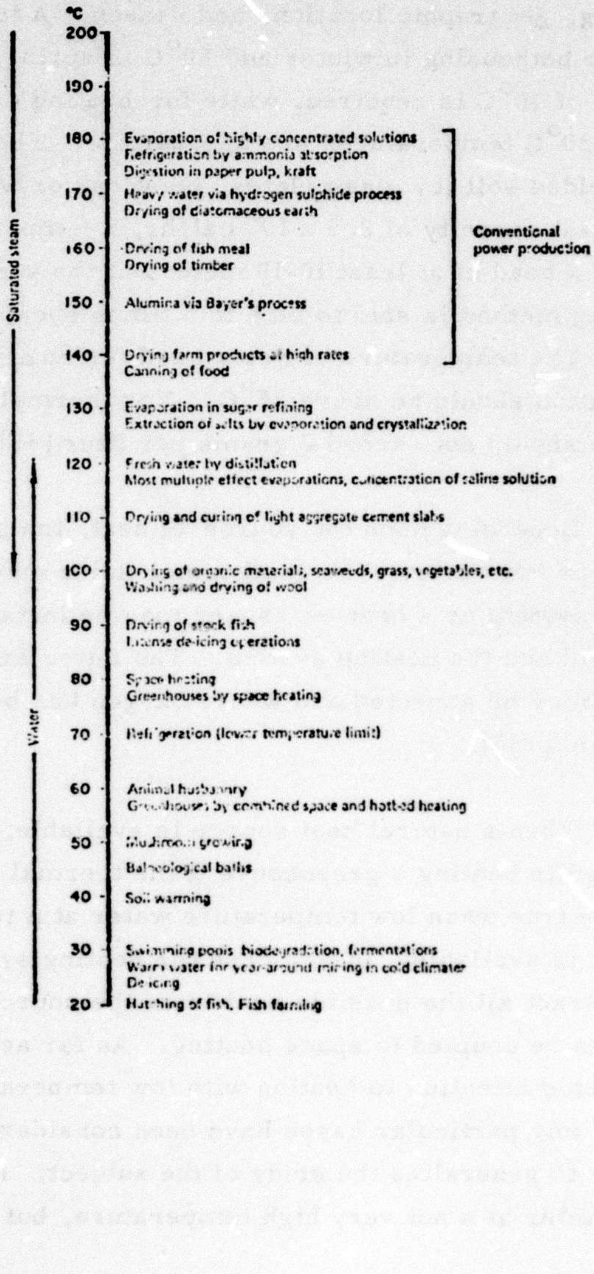
Much depends on a systematic and imaginative search for new applications that is carried out continuously, and that it is kept in mind that the low cost of geothermal energy opens up new possibilities that may be unattainable for the more conventional sources of energy [136].

In the following table some applications have been arranged against a scale of temperature to illustrate diverse use of geothermal sources [78].

Additional information on developments of geothermal resources in specific fields will be discussed in proceeding subchapters.

1. Agriculture

Agricultural use of geothermal waters for hotbed and hothouse cultivation of vegetables and flowers has increased considerably in recent years. It has been estimated, that one hectare (2.47 acres) of heated soil


°C
200
190
180 Evaporation of highly concentrated solutions
Refrigeration by ammonia absorption
Digestion in paper pulp, kraft
170 Heavy water via hydrogen sulphide process
Drying of diatomaceous earth
160 Drying of fish meal
Drying of timber
150 Alumina via Bayer's process
140 Drying farm products at high rates
Canning of food
130 Evaporation in sugar refining
Extraction of salts by evaporation and crystallization
120 Fresh water by distillation
Most multiple effect evaporations, concentration of saline solution
110 Drying and curing of light aggregate cement slabs
100 Drying of organic materials, seaweeds, grass, vegetables, etc.
Washing and drying of wool
90 Drying of stock fish
Intense de-icing operations
80 Space heating
Greenhouses by space heating
70 Refrigeration (lower temperature limit)
60 Animal husbandry
Greenhouses by combined space and hotbed heating
50 Mushroom growing
Balneological baths
40 Soil warming
30 Swimming pools, biodegradation, fermentations
Warm water for year-around mining in cold climates
De-icing
20 Hatching of fish. Fish farming
Conventional
power production
Saturated steam
Water

will produce year-round vegetables for a town with a population of 10,000 and for a twon of 100,000 about 10 hectares will be required [32].

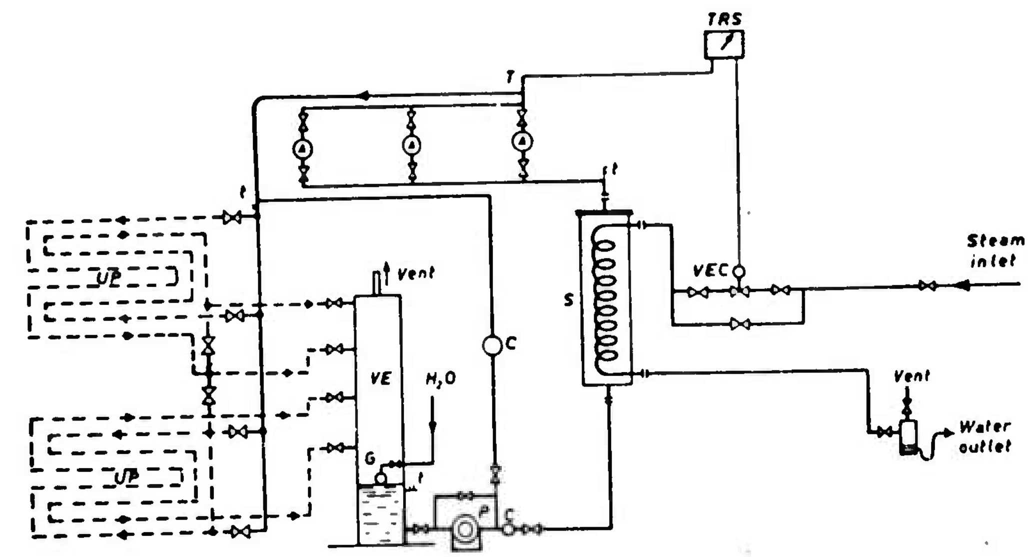
In general, the water temperature varies according to the type of farming, geographic location, and season. A temperature of 60°C is required for hothousing in winter and 50°C in spring; for heated hotbeds, a temperature of 40°C is required, while for heating of soil (sheltered or unsheltered), 30°C temperatures are appropriate. The thermal water for heating of shielded soil (by glass plates, plastics, or wooden boards), should have natural heat capacity of 2.5×10^6 cal/hr, a temperature between 35 and 40°C, and a head of at least 10-15 meters at the surface. Heating soil by the shielding method is said to be 4 to 5 times cheaper than by hothousing installations. The temperature of water used for heating soil and for thermal irrigation should be above 25°C. For thermal irrigation, the mineralization should not exceed 2 grams per liter [33].

Depending upon the source of heat, the greenhouse may use natural steam or hot water. The geothermal fluids may be applied directly in the heating system or a heat exchanger may be installed between the geothermal fluid and the heating system. The latter arrangement is practiced where scaling may be expected and where oxygen has been entrained in the geothermal fluid [135].

When a natural heat source is available, no relevent problems are encountered in heating a greenhouse if the thermal content is high. The same cannot be true when low temperature water at a temperature between 30°C and 70°C is available. In this case the heating system should be carefully designed to extract all the possible heat from the source. To achieve this, soil heating can be coupled to space heating. As far as it is known, only the USSR has paid attention to heating with low temperature waters. It seems, however, that only particular cases have been considered and that no attempt has been made to generalize the study of the subject. In fact the number of sources with water at a not very high temperature, but still not low enough

to be wasted, is enormous all over the world. Therefore, it is worthwhile to study the possible conditons that can be obtained at different temperatures of the heating water and heating systems. The aim then is to determine the best working conditions for an available source's given temperature and the limits within which the different cultivations are possible.

Fig. 24 and Fig. 25 are schematics of a pilot low-cost greenhouse heating system and the layout of the underground pipes.



A = Unit Heaters
C = Water Meters
G = Float Valve
P = Circulating Pump
S = Heat Exchanger
t = Thermometer
T = Temperature Transducer
TRS = Thermostat
UP = Underground Polyethylene Pipes
VE = Expansion Tank
VEC = Motor Operated Valve

Fig. 24. Schematic of a pilot greenhouse and hookup of the heating system [133].

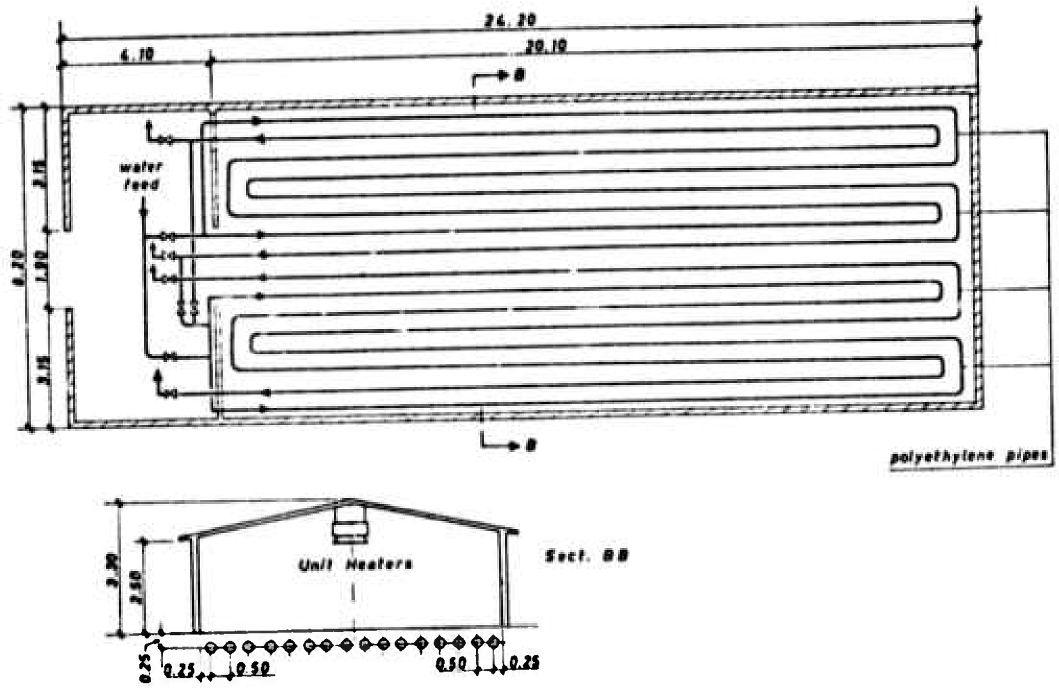


Fig. 25. Layout of the underground heating pipes for a greenhous (dimensions in m.) [133].

The purpose of a pilot greenhouse is to obtain data used for the construction of low-cost modular units. Particular attention will be focused on the following points: importance of the soil heating, heat exchange between polyethylene pipes and soil, relation between soil mean temperature and minimum or maximum water temperature for efficient heating, amount of heat needed for different cultivations, limit soil temperature for best efficiency, and minimum temperature and water flow necessary for heating [133].

A number of experimental greenhouse installations are operating in various parts of the USSR. Quite often these are parts of combined schemes, where the systems also supply heat for house heating and especially for soil heating, which is a novel and interesting application of geothermal energy. The units can be quite large, up to 15 hectares (150,000 m^2) of greenhouses combined with 1.5 hectare (15,000 m^2) of heated soil. Peak heating with boilers seems to be used frequently. An agricultural application is using the waste water from the Pauzhetka geothermal power station for heating 80,00 m^2

of greenhouses which will provide about 2,000 to 2500 tons of vegetables annually. However, a large scale development of agricultural uses of geothermal energy is predicted in the USSR for the near future [136].

A novel development in New Zealand is growing mushrooms by geothermal heat. The soil is sterilized by the heat and the mushroom houses are kept at the right temperature and humidity by using the geothermal fluid directly and without the use of heat exchangers. There is also a tree nursery where seedlings are raised in greenhouses and shelters, which are used for thermal sterilization of soil.

In the U.S., field experiments were conducted in 1969 near Corvallis, Oregon to measure the effect of soil warming. The yield of corn silage increased by 45%, tomatoes increased by 50%, soy bean silage increased by 66%, and beans increased by 39%.

In dairy farming there are many interesting applications of natural heat, such as the production of dried milk, casein, sucrose, hatching eggs, and to help biodegradation of the wastes from pig sties [78].

In conclusion, geothermal energy is used for various agricultural applications, such as husbandry, growing of various vegetables and flowers, drying of timber, seaweeds, grass and farm products, as well as washing and drying of wool, and breeding of alligators.

2. Industry

Regarding industrial applications, geothermal energy may be used in a number of ways in various industrial fields such as simple process heating, drying or distillation in every conceivable fashion, refrigeration and air conditioning, or de-icing or tempering in various mining and materials handling operation. Geothermal fluids may themselves also furnish useful raw materials in some cases. Some thermal waters contain salts and other valuable chemicals, while the steam may contain some industrially useful noncondensable gases.

The amount of steam which may be applied per unit weight of product in a number of industrial processes is shown in the following table, indicating specific consumption of steam and the steam used per dollar value (1973) in some established processes.

Product and process	Steam requirements lb steam/lb	Product value cents/lb	Steam per unit product value lb steam/ $value
Heavy water by hydrogen sulphide process	10,000	3,000	333
Ascorbic acid	250	250	100
Viscose rayon	70	75	93
Lactose	40	14	286
Acetic acid from wood via Suida process	35	10	350
Ethyl alcohol from sulphite liquor	22	7	314
Ethyl alcohol from wood waste	19	7	271
Ethylene glycol via chlorohydrin	13	13	100
Casein	13	56	23
Ethylene oxide	11	15	73
Basic Mg carbonate	9	11	82
35% hydrogen peroxide	9	18	50
85% hydrogen peroxide from 35% H_2O_2	4¾	—	—
Solid caustic soda via diaphragm cells	8	3	266
Acetic acid from wood via solvent extraction	7½	10	75
Alumina via Bayers process	7	3	234
Ethyl alcohol from molasses	7	7	100
Beet sugar	5¾	10	58
Sodium chlorate	5½	9	61
Kraft pulp	4 1/5	6	70
Dissolving pulp	4 1/5	—	--
Sulphite pulp	3½	6	58
Aluminium sulphate	3½	2	175
Synthetic ethyl alcohol	3	7	43
Calcium hypochloride, high test	3⅓	3	111
Acetic acid from wood via Othmer process	2¾	10	28
Ammonium chloride	2¾	6	46
Boric acid	2¼	5	45
Soda ash via Solvay process	2	1½	133
Cotton seed oil	2	10	20
Natural sodium sulphate	1 4/5	1½	120
Cane sugar refining	1 2/3	10	17
Ammonium nitrate	1½	3½	43
Ammonium sulphate	1/6	1½	11
Fresh water from sea water by distillation	1/12	1/60	500

Most of the values for steam consumption in the first column are quoted from Chilton (1960) and represent common industrial practice. It should be noted that the values for steam consumption are based on the use of fossil fuels, and may not give correct indications of the possible use of geothermal steam. But the conventional steam consumption per unit weight of product does not give a satisfactory measure of its importance in the production process. A much more reliable indicator is the amount of steam used per unit value of the product shown in the third column. For reference,

the product values are recorded in the second column of the table in terms of U.S. cents per pound according to recent listings, where available. However, it is not likely that any possible economics in steam-consuming processes based on present practices in the established industries will yield more than a fraction of the possibilities of geothermal heat [78].

A survey in the U.S. has shown that of all the energy which goes into the processing industries, more than 80 percent is used for process heat, and less than 20 percent for electricity. Similar conditions may be found in other countries where electrical process industries are not especially dominating. The process industries, however, use both high and low-temperature heat: the high ones usually being produced by a direct flame, and the low ones generally by steam. Apparently, about 50 percent of the total process heat is used within the range of steam temperatures in such fields as for petroleum refining (steam and direct fire), pulp and paper manufacturing, food processing (canning and preserving), corn products, and sugar refining. Most of the steam is of low temperature and pressure which is suitable with geothermal steam. Steam in the low pressure range may be used specifically for boiling, sterilizing, drying, evaporating and heating of process materials. Because of the local character of the natural fluids, their successful use is to a greater extent dependent on the availability of raw material close to the source. However, because of the low cost of this healing energy, it may be possible to use raw materials which could not economically exploited otherwise. In other cases a less expensive design of equipment may be adopted to reduce consumption of heat.

Geothermal fluids differ in usefulness as a heating medium. Saturated steam at 150-200°C has potentially the same possibilities as the usual fuel-generated medium, but it contains gas which may affect heat transfer and cause corrosion. Steam at temperatures of 100-150°C has a more limited use in industry, but the corrosion danger is less than at the higher temperatures. Hot water below 100°C may be used only for drying and some more limited industrial applications [52].

Process heating is a possible market for geothermal energy, but development in this field is impeded by the low transportability of geothermal energy, as well as the availability of necessary raw materials. The geothermal resources are generally located in areas without supply of raw materials suitable for economical processing by low-temperature fluids. In general, the transportability of the geothermal energy is less of a problem than existence of possible raw materials [8].

Experience in Italy, Iceland, California, Mexico, and New Zealand shows that under favorable conditions geothermal heat can be produced at very low cost. The production cost of natural steam delivered to power plant, in some of these areas, has been about $0.25 metric ton (1970), which is about 1/5 of the lowest possible cost of steam derived from fuel. Of course, due to low temperature and pressure, the exergy* (capacity of the unit mass of the steam to produce mechanical work) of natural steam is only about 1/2 of the energy of steam from fuel. Therefore, the most economical uses for natural steam are in industry where ther is a need for power and heat [25].

Consideration will now be given to some examples of current practice in this field, as well as further industrial applications which are being investigated and developed.

The pulp and paper mills in New Zealand were the first major industrial development to use natural steam. Most wood pulp manufacturers also produced finished paper from pulp. Another use of wood pulp is for the manufacture of viscose rayon. Timber seasoning and veneer fabrication by natural heat also appears to be common.

A very interesting application of geothermal energy is found in sugar processing; production of raw sugar and its refinement. Another

---

* The exergy concept is now used in modern literature in thermodynamics.

closely related field is found with fermentation processes based on molasses. Among the products are ethyl alcohol, butanol, acetone and citric acid, all of which may benefit from geothermal steam. It is reported that natural heat is already used in Japan for brewing and distillation.

Another possible application for natural steam is in the production of alumina from bauxite. This possibility was studied in Iceland some years ago but was not put into practice owing to unfavorable raw material and market conditions.

Considerable size of elemental sulphur deposits are now being studied in New Zealand and it is hoped that geothermal steam may help by providing process heating in the refining of the ore. In addition, elemental sulphur on a small scale is being recovered directly from the fumes of a volcano in Japan [78].

Processing of sugar, rice, coffee, and other crops should be considered in some of the Central American countries where geothermal resources are abundant as the raw materials.

In general, whereever industrial raw materials needing drying, cooling, distillation, fermentation and other relatively low temperature heat treatment, geothermal energy can probably be used with considerable economic advantage [136].

The following subchapters outline some major industrial fields using geothermal heat or steam for processing and development.

a. Chemical by-products

Geothermal waters are enriched with about 80 different chemical elements, which can be extracted either coincident to the purification processes of thermal waters intended for geothermal electric power stations and other facilities, or specifically for the chemical industry [33, 44].

Frequently, hot and superheated geothermal waters contain large amounts of salt, iodine, bromine, naphthenic acid (mixture of cycloparaffin acids), boron, strontium, lithium, fluorine, and other rare elements, which can be extracted easily for the chemical industry [44].

The extraction of sodium and magnesium sulphates, iodine, and bromide from geothermal waters has been carried out in the Soviet Union. For example, in the Kashkadar'insk artesian basin (Uzbek SSR) from only one exploratory well, about 2,700 tons of salts (mostly potassium chloride), 9 tons of bromine, and about 100 kilograms of iodine have been extracted in one year [45, 46].

Recently, the Soviets announced that techniques for the extraction of boron, alkali and alkali-earth metals, and trace elements are being developed [46].

In recent years much attention is being given to the study of the mineral content of thermal waters which do constitute an important portion of subsurface hydrosphere. This interest is explained by the fact that the possible utilization of such waters, either their heat or valuable chemical components, is for the national economy.

Only those areas may be of potential geothermal importance, either in the field of balneology or in the commercial sphere (with iodine, bromine, boron, potassium or lithium bearing waters) characterized by particular geological, thermal and geochemical features. Generally, these areas are represented by folded belts or zones of recently extinguished volcanic activities.

Chloride waters, rich in salts, and revealing high concentrations of bromine, potassium, lithium and strontium are being formed through halogen formations found throughout the sedimentary sequence.

Concentration of bromine, strontium, lithium and rubidium increase with depth of occurrence in thermal waters and rising mineralization, while boron and iodine show a reverse regional dependence i. e., their concentration decreases with depth and rising mineralization [138].

Many high-temperature geothermal areas have some deposits of elemental sulphur. Although this kind of sulphur used to be mined centuries ago, and is still mined intermittently in some parts of the world, it is not very important today due to the small and scattered deposits. However, one such deposit of considerable size is now being studied in New Zealand, and it is hoped that geothermal steam may help by providing process heating in the refining of the ore.

There are plans for extracting common salt, calcium chloride, potassium chloride and bromine from geothermal brine in southwestern Iceland. This project is now in the last stage of preliminary exploration.

Some thermal waters in the USSR have a high content of bromine and iodine, but the present production satisfies normal requirements. Interest is also shown in alkaline metals, boron, lithium, and a number of trace elements.

Very interesting possibilities with minerals exist in Uganda, where many thermal springs contain a significant amount of sodium bicarbonate.

In general, CO_2 is the predominant component of the noncondensable gases, H_2S is usually the second, elemental hydrogen the third, and there are also small amounts of methane, nitrogen, ammonia and argon. The amount of these materials in the steam depends on many geological conditions. However, the amount seems to vary between 1 and 10 liters of total noncondensable gas per kg of steam in the great majority of cases, where steam is harnessed for any length of time. The greatest experience in utilizing these gases was

obtained in Larderello, Italy, where these gases were recovered for many years from steam used in the production of electric power. Besides boric acid, ammonium bicarbonate, ammonium sulphate and sulphur used to be recovered, but by 1970 no such production was mentioned by Italian sources. The only known record of present use of these gases comes from Japan, where sulphuric acid is produced from gases at the Otake geothermal power plant. But even if these gases are of small importance compared to the energy, they may very well be of economic value in some localities, especially if the steam is used for industrial purposes. Such activities often require sulphur or sulphuric acid and sometimes carbon dioxide.

There are several reports on a new process being developed for the production of magnesium chloride and soda ash from seawater and salt. Magnesium hydroxide is precipitated out of the sea by brines, as in current industrial practice. Geothermal heat would be very suitable for this purpose, and the process is being developed with that in mind [78].

The modern technique to separate chemical compounds by precipitation and crystallization, whenever concentration and temperature are right, is still very new. This technique is slowly replacing the presently employed analytical precipitation techniques in which chemical reagents of any sort are added, thereby complicating given solutions and also increasing some of the recovery problems. We are just on the threshold of opening up new mineral resources in brines. But because of the cheap waste heat available with the geothermal brines it seems that the mineral extraction can be accomplished in these cases more economically and more efficiently. Furthermore, in some cases the value of the minerals often superceeds the value derived from the sale of power and makes various projects viable [139].

However, up to present time, little appears to have been achieved with regard to the extraction of minerals from waste geothermal brines. Any financial advantages arising from such a system could help to offset additional costs which might occur due to the increasing difficulties of effluent disposal. Most geothermal waters contain many minerals, some of which cause severe effluent disposal problems. A multipurpose approach to

future geothermal planning and development may discover that some of these minerals are capable of economic use when viewed within the context of overall resource exploitation. However, no generalization can be made since each location must be judged on its own circumstances which embrace steam condition, water mineral concentrations, local demands for both water and minerals, together with basic economic data such as interest rate and labor productivity. Nevertheless, the multipurpose approach to the utilization of geothermal energy resources will probably be more prevalent in the future, bringing with it substantial overall gains [129].

b. Heating and hot water supply

The economic use of geothermal water for heating depends on the selection of appropriate heating system, the discharge capacities of wells, and the temperature and chemical composition of the water.

In case the chemical compositions are beyond permissible limits, the thermal water before entering the heating system; should be passed through a degasifier and heat exchanger. In the heat exchanger, the thermal water releases its heat into low-mineralized and chemically nonaggressive water, and then is used for the heating system. For highly mineralized thermal waters, a centrifugal separator is required to separate the steam from water before it is introduced into the heating system. In general, geothermal water should not have more than 0.1 mg/l of oxygen, 5 mg/l of sediments, and 700 mg-equiv/l of hardness (carbonate residuals) [33].

Space heating can be carried out by means of water at a temperature as low as 50°C. Also process heating in the cehmical industry would in most cases require steam or water at temperatures around or above 100°C. It is therefore clear that space heating is a very suitable market for geothermal energy. However, the low transportability of the geothermal fluids constitute the greatest difficulty in space heating. This is demonstrated by the fact that one kilogram of natural steam at one atmosphere abs. and 100°C contains only 540 kilogram calories of latent heat.

Natural steam, used on a large scale, can be transported economically over a maximum distance of 10 km, and natural hot water can be transported for space heating only about 75 kilometers [8].

Geothermal energy for heating has certain inherent characteristics that have to be taken into consideration whenever a geothermal heating system is planned and designed:

- the thermal fluids have a fixed temperature in each thermal area,
- each borehole has as a rule a constant output,
- the cost of the energy produced and/or delivered to the consumer is predominantly capital costs (depreciation, return on capital, etc),
- the transportability of geothermal fluid is limited,
- the chemistry of the geothermal fluid must be observed, and
- the unit cost of the energy produced and delivered is dependent on the capacity of the system.

In general, every district heating project must be designed for the climate of the site. The most significiant characteristic of the climate in this respect in the variation of the daily, mean outside temperature over the year. Attention must also be given to the diurnal variation of the outside temperature, and the effect of such factors as wind velocity and solar radiation. The objective is to maintain a constant optimum room temperature in the heated building (for instance 20-20^{o}C for apartments). The building receives, in addition to the heat supplied by the system, a certain amount of free heat, i.e., heat lost by the occupants, electric lighting and appliances, solar radiation, etc. Thus the power required for heating is directly proportional to the difference between the inside design temperature and the outside temperature.

The most practical solution is usually to install additional facilities for peak heating of the water by fossil fuels or electricity as required, or perhaps in combination with both methods. This has been done in Iceland, Japan and USSR. The amount of energy requirements of the coldest days is so small in comparison with the annual energy needs that the use of expensive peak heating equipment is fully justified.

At the present state-of-the-art, geothermal power stations operating with two phase flow have a very low factor of energy utilization, which means that they supply enormous amounts of waste energy. Wherever possibilities permit, this should be used for district heating, agricultural or industrial purposes. Combined schemes allowing the use of excess water for heating of greenhouses and especially for soil heating are practical measures for improving the annual load factor [141].

Geothermal water for heat supply can be used in four different schemes: direct thermal water utilization, with peak-load boiler room, with thermal masses, and in a combined scheme.

Among the possible schemes of direct thermal water utilization, the most effective are the following: two-stage parallel switching of heating and hot water supply installation (Fig. 26A), and successive switching of panel and air heating systems as well as hot water supply systems (Fig. 26B). These schemes provide the deep cooling of thermal water. However, the coefficient of well heat output which is very low, can be attributed to the irregularity of the heat load schedule. The advantage of the direct thermal water scheme is its exceptional simplicity and possibility of automation.

Direct geothermal water use is only possible in cases where its temperature is up to the consumer's demand. In areas of old buildings, the water temperature should be not below 90°C, and in areas of recent construction, water with temperatures of 60-70°C can be used in a direct scheme. If the geothermal water does not have required temperatures, it is advisable to use peak plants with additional heating to reach the required parameters and allow the coefficient of the well heat output to be increased.

The well in this case is regarded as the basic source with a uniform annual load. However, the most effective may be combinations of the above schemes of direct thermal water and peak boiler rooms (Fig. 26C).

To raise the geothermal heat temperature, heat pumps can be used all year-round in winter for heat supply, and in summer for cold supply. It is unsuitable to use heat pumps only for heating or as peak plants. Among possible schemes of heat pump for heat and cold supply, the most effective are multistage installations (Fig. 26D). An example of the combined scheme is the one including geothermal well, heat pump installation, and peak boiler room (Fig. 26D). However, economical indices of this scheme are rather high [115].

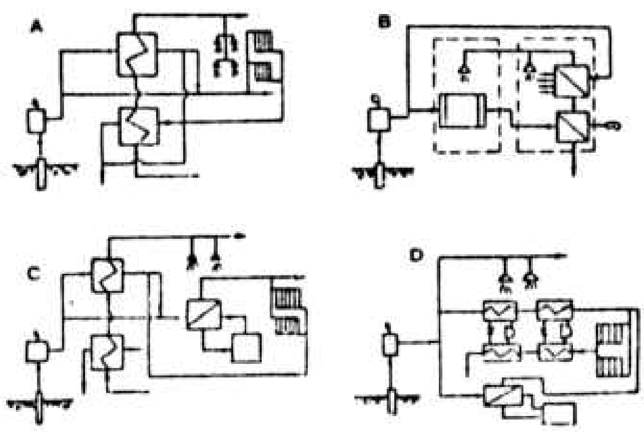


Fig. 26. Schemes of geothermal heat supply systems. A- two-stage switching of hot water supply and heating installation; B- successive switching of panel and air heating and/or hot water supply systems; C- scheme of peak load boiling room; D- scheme with multistage heat pump [115].

Regarding heating systems, among the most interesting is that used by the town of Paratunka, Kamchatka, to heat three 48-unit apartment houses. The maximum load is 0.55 Gcal/1, and geothermal water at 80°C

is used for heating both the tap water and the apartments. A conventional radiator system or radiant heating with pipes embedded in the floors or ceilings is used, and the heating system is designed for a temperature drop from 80 to 40°C. Utilizing a heat pump, part of the 40°C return water can be reheated to 60°C by extracting heat from the remainder of the return water, which in turn is cooled to 10°C. The 60°C water is mixed with the 80°C geothermal water. The temperature of this mixture can be increased as desired by an electrical peak heating unit. Increased loads during cold spells can also be met by increasing the heat extraction from the geothermal water with the heat pump [140].

In New Zealand, geothermal fluid is used as a means of cooking in what are known as "hangis". These have been developed from the ancient Maori method of cooking by steam, produced by covering heated stones with native mats which were soaked in water. Food to be cooked was placed in the mats, covered with similar mats and overlaid with sand to conserve the generated vapor. Modern hangis (Fig. 27) are constructed from metal or concrete. A discharge pipe is taken from a well through the hangi. By throttling of a control valve on the outlet of the pipe flash, steam will enter

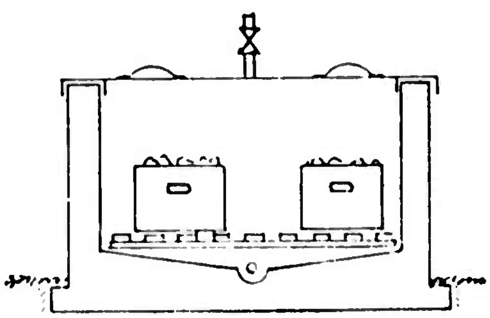


Fig. 27. Cross section of a typical hangi [134].

the hangi through holes drilled in the pipe and fill the hangi with steam under atomospheric pressure. Food cooked in hangis in excellent and as the ste m is at atmospheric pressure, food is nver overcooked or spoiled. Many hotels and hostels in New Zealand use this method of cooking [134].

Hot water from geothermal springs and wells with moderate temperatures and of required chemical composition are being used extensively for domestic, industrial, and other hot-water supply. To meet required specifications, the chemical compositions of geothermal water should not exceed 1 g/l of dry residuals, 0.5 g/l of sulfate, 0.35 g/l of chloride, and 7 mg-equiv/l of average hardness. Besides the required clarity, taste, and odor contaminants should be within the established norms. In addition, the content of lead should not exceed 0.1 mg/l, while arsenic, fluorine, copper, and zinc should not exceed 0.5, 1.5, 3.0 and 5.0 mg/l, respecitvely [33].

Hot water supply systems are constructed using conventional techniques and equipment and, in many cases, in conjunction with heating systems.

c. Heavy water production

The production of heavy water has interested scientists working with geothermal energy for more than two decades, but for various reasons no such plant has yet been built [78].

The separation of heavy water from ordinary water is a high energy-consuming process and in some respects the ideal chemical process for utilizing geothermal steam as process heat. A calculation has been made on the manufacutring cost of heavy water by the H_2S/H_2O ion exchange method with geothermal steam supplying the process heat. The results of this calculation show that heavy water produced in such a manner would be 10-15 percent cheaper, than produced with heat derived from natural gas or from exhaust steam from conventional turbine [36].

Therefore, the production of heavy water (D_2O) by the dual temperature H_2S process is one that should constitute the best market for geothermal energy. The raw material is water and the price of the product is very high. The consumption of heat by the process is exceptionally high, i.e., about 6000 units weight of steam per unit weight of the product. The available steam has to be at about 6 atmospheres abs. [8].

The characteristics of geothermal steam cause modification in the optimization of the heat recovery system of a heavy water plant, namely that low cost leads to a lesser optimnal degree of heat recovery and the price vs steam temperature make it economical to split the heaters into low and high temperature sections. The relatively low pressure of geothermal steam make it necessary to strip the H_2S from the waste water at a lower pressure than the main process pressure. This in turn leads to a modification of the process and the introduction of an absorber in the feed water stream where the H_2S stripped from the waste water is returned to the system to minimize compression work. The cost of heat delivered to the process will be further reduced by a factor of two, if the water accompanying the steam from the borehole can also be used. But this is still uncertain because silica and other solids in the hot water may lead to scaling in the heat exchangers.

In the late fifties, when the trend in reactor development was still somewhat unclear, the outlook for the heavy water market was quite optimistic, and various countries contemplated erecting heavy water manufacturing facilities. Numerous studies were undertaken, often with duplicative efforts because of the secrecy that still prevails in the nuclear field. As a result, the slightly enriched light water moderated pressurized water and boiling water reactors became the most economical, and the expected heavy water market never materialized. This may be partly due to the fact that the leading nuclear powers in the military sense, primarily the United States, were also the leaders in reactor development. As these nations had enriched uranium as a by-product of their weapons program, it was relatively inexpensive and easily available to them for use in reactors. Thus, it may be debated whether or not the military programs of the nuclear powers did not really subsidize light water moderated reactors.

In general, in reactors where natural uranium is used, heavy water moderation offers the best neutron economy. This is especially important in converter reactors which will ultimately provide an independent source of highly enriched fuel. For the reasons outlined above, many nations are taking a second look at natural uranium heavy water moderated reactors,

and the outlook for the heavy water market is brightening again. Estimates made in Canada and Sweden indicate that if no new production facilities are erected, there will be a shortage of heavy water by the late seventies [36].

The use of geothermal steam for the production of heavy water has been under consideration in New Zealand since 1960 [136]. A study carried out by the Iceland Nuclear Science Commission indicates that it should be possible to operate a large heavy water production plant utilizing geothermal steam. The estimated price of the product is considerably below that operated by conventional fuel [8, 145].

In conclusion, a large heavy water plant utilizing the hydrogen sulfide water isotope exchange process is still the most economical and that this process should be used in conjunction with geothermal steam [36].

d. Permafrost, mining and construction

The Soviets foresee future large-scale use of geothermal waters in mine heating to facilitate the exploitation of mineral resources in permafrost, frozen soil, and regions subject to long and severe winters [42]. In Magadan Oblast', the main gold mining region in the Soviet Union, scientists are studying methods for year-round hydraulic placer mining with geothermal waters. Similar methods are under consideration in the mining of diamonds, lead, tin, wolfram and other minerals abundant in the Taymyr, Yakutia, Kolyma, and Chukotsk regions, all in the northeastern part of the USSR.

A study conducted by the Leningrad Mining Institute indicates that for this type of mining, the thermal water should have a temperature between 20 and 30°C and a minimum discharge of 250 cubic meters per hour [33].

The most interesting and important future roles of geothermal energy is in upgrading of minerals. The process heating available from geothermal fluids may even be o. such importance that mineral deposits which were hitherto worthless may become economically attractive. Such is the case with the recovery of diatomaceous earth in Iceland [78]. A diatomite plant

near Myvatn, Iceland, has two principle operating sections: the wet end which receives the wet diatomaceous earth from the lake and produces dry diatomaceous earth, and the dry end which turns the dry diatomaceous earth from wet end into commercial diatomite filter aids. Geothermal steam is used for preheating the feed to filters which dewaters the raw material and also for drying in rotary steam tube dryers [142].

There is a minor, but quite important, use of geothermal heat for curing of light aggregate cement building slabs [78].

Possibilities also exist for utilizing geothermal waters for various types of construction in permafrost and frozen soil. Applied thermal water creates a hot slurry which, through gravity, penetrates into the frozen soil and facilitates drilling of holes for pillars and other foundation components [33].

e. Refrigeration and air conditioning

Geothermal waters are a very cheap source for refrigeration and air conditioning in domestic, public and industrial installation, with great savings of over hundreds of thousands kilowatts of electric energy possible. Geothermal waters with temperatures above 13°C provide better results for year-round air conditioning applications. Thermal waters of 70°C require special conversion equipment. To obtain temperatures above 0°C, special lithium-bromide machines are in use, and for temperatures below zero, the ammonia-water machines are appropriate [43].

The lithium-bromide absorption machines of 2.5 Gcal/h for operation on geothermal water are being manufactured in the USSR to meet the great demand for refrigeration in various chemical industries, such as synthetic rubber, ammonia and metallurgical plants.

Some preliminary studies in Iceland indicate the possibility of using absorption refrigeration powered by geothermal energy for production of liquified air or nitrogen for use in food processing and in transportation. This confirms that liquidifed nitrogen could be competitive with ice as a cooling

agent. This could also be of interest for other industries such as metallurgy, which uses large quantities of liquid oxygen.

Another related process using both heat and cold where geothermal energy seems ideally suited is that of freeze-drying of foodstuffs, such as coffee, fruit juices, mushrooms, shrimps, soups, etc. [136].

The most interesting installation is the geothermal heating and air conditioning system of Rotorua International Hotel, New Zealand. The system is designed for the extreme climatic temperatures from -4°C to +30°C. A 130 ton (0.39 Gcal/h) lithium-bromide absorption unit supplies the cooling for the air conditioning and requires a heat input of 0.575 Gcal/h. The specific energy requirement of the absorption unit is therefore 1.47 kcal heat per 1 kcal of cooling [141 & 143].

Utilizing geothermal sources there should be an opportunity for improving the annual load factor in continental climates by the introduction of comfort cooling. Also it is questionable whether an economic basis can be found for district cooling systems in the tropical parts of the world. The tropical countries have an urgent need for cooling in connection with food processing and storage, and other industrical uses for cooling with geothermal energy. Combined comfort cooling and industrial schemes might therefore be feasible in the tropics [141].

f. Salt extraction

Presently, the only recognized source of salt is sea water. There are historical indications of some salt-making activities in Iceland in the ninth century. A serious attempt was made in the eighteenth century to produce salt from sea water on a large scale with the aid of geothermal hot water.

The extraction of salt from sea water by multiple effect evaporators with subsequent crystallization in vacuum pans using geothermal sources appears very favorable in some respects. The fundamental difficulties, however, lie in the nature of the source of the salt, for one ton of salt must be

extracted from 35-45 tons of sea water and the exact amount depends upon the yield from the process adapted. It is obvious that the greatest chance of finding a suitable process for salt extraction from sea water under the above mentioned conditions would involve the use of geothermal steam as the main source of energy.

The extraction of salt from seawater involves two main operations: the removal of water to saturate the solution with respect to sodium chloride, and the crystallization with the finishing of the product. These processes are well known and widely practiced with solar energy in some warm countries, but a different approach must be made if geothermal steam is used [144].

The Ikeda Geothermal Saltmaking Plant, near Shikabe village, Hokkaido, Japan, is provided with an open-air heating tank, roofed concentration tank, and a refining building in a site area of about 2000 m^2, into which hot water and steam are introduced from a well for heating of seawater. This plant produced one ton of salt daily, or about 300 tons annually. However, as reported in 1970, this plant will expand for a production of 100,000 tons annually. The plant will employ a multistage effective vacuum distillation unit also used for producing fresh water from seawater together with an ion exchange film electrolytic dialysis unit. The concentrated salt water will be refined and used as table salt [103, 136].

In Iceland, a novel scheme for extracting salt from seawater is in the planning stage by using a combination of glacial ice and geothermal heat. In addition, several studies consider utilization of geothermal brine of marine origin as an independent source of salt, and in combination with operation of the selective production of other minerals from seawater [145].

g. Water supply (distillation or desalination)

The possibility of using geothermal energy for the production of fresh water has been raised several times in the past. It is pointed out that the fresh water may either come from an outside source or originate in the

geothermal fluid itself. Since the practice of purifying water from an outside source by distillation is already highly developed, natural steam could undoubtedly be used instead of conventional steam.

When ground reservoir temperatures do not exceed about $100^{\circ}C$, the extent of mineralization may be so low that the water is potable. Warm springs include many of the most famous health mineral springs in the world, where the water may be bottled for distribution.

In the case of high enthalpy fluids, the water is not directly potable owing to the presence of contaminants. However, this water contains enough energy for self-evaporation and may yield inexpensive water conversion [78].

Desalination of low-temperature waters involves more chemical and effluent-disposal problems, since the dissolved solids are concentrated into a small proportion of residual water. Soluble constituents, such as NaCl, normally will not precipitate, but constituents of low to very low solubility, such as SiO_2, $CaCO_3$, and $CaSO_4$, are potentially troublesome [17].

Averting projected water shortages has become a serious problem in many places of the world. Importation, reclamation, and desalination systems are proposed as solutions, but all take large amounts of power. Interest has been focused recently on geothermal energy, since it appears to be a potentially clean source of large amounts of power. Relatively small scale geothermal power and water production have been carried on in several parts of the world. In these systems water carries thermal energy from the reservoir to the surface, and condensate from steam turbines may be available. as a fresh water supplier. Since liquid water produced from geothermal wells is generally saline, distillation is a means of making more fresh water available. For geothermal development, hot water dominant systems presently appear to be the most important, as they are the most readily available and offer the greatest potential for water and power production.

There are several distillation processes which will be only mentioned, without detailed outline of operation. The multiple-effect distillation, in which each effect takes place at a lower temperature than the preceding one, is one of the oldest and best desalination methods. Another distillation method that has been proposed for desalting of geothermal brines is the multistage-flash process in which hot brine is passed through a series of chambers, each chamber at a lower pressure than the preceding one. This is probably the best developed desalination technique and over 90 percent of all desalination in the world is performed by this process [132].

However, the use of geothermal heat for desalination purposes has not yet been put to the practical test, but the possibilities of doing this have been widely discussed [95].

There are opinions that geothermal fluids could serve not only as the "raw material" of water, but also as a source of heat which could be used either for the self-distillation of contaminated hot waters or for the desalination of sea or brackish waters. However, at this time, it is too early to predict the outcome of various studies on water desalination for agricultural use, but there are indications that geothermal energy is the cheapest available for this purpose [37, 38].

3. Medical and recreation

Over the years, geothermal waters have been used by clinics, hospitals, and health resorts in many countries for therapeutic purposes.

Based on medical research and empirical experience, geothermal waters with their chemical components have a significant healing effect on various human maladies. The basic indicators for the therapeutic value of thermal waters are: mineralization, ion content, gas saturation, gaseous components, content of specific biologically active components (CO_2, H_2S, As, Fe, Br, I, H_2SiO_3), radioactivity (Rn), hydrogen ion concentration (pH), and water temperature. To be considered for balneological use, geothermal

water should meet the following norms: overall mineralization 2 g/l, content of soluble CO_2 - 0.5 g/l (for external application, 1.4 g/l), content of H_2S - 10 mg/l, As - 0.7 mg/l, Fe - 20 mg/l, Br - 25 mg/l, I - 5 mg/l, H_2SiO_3 - 50 mg/l, and Rn - 5 mμ Curie/l. However, the above-stated content of As, Fe, Br and I pertain to therapeutic drinking water with an overall mineralization of 10 grams per liter. Thermal waters for swimming pools and baths should have a temperature between 25 and 40°C, and mineralization not exceeding 50 grams per liter [33].

Hot springs and warm mineral spring have been used for recreational and health purposes in many countries as long as historical records are available. However, a distinct change has occurred in recent years in that such places have become more accessible due to better communications and newer hotels. There are records of many geothermally-heated swimming pools, mineral baths, mud baths, steam baths, and specially organized recreational centers from several countries. However, these applications of natural heat have been developed furthest in Japan, where hot springs have been used for this purpose from ancient times [78].

4. Pisciculture

Fish farming utilizes geothermal fluids of lower temperature, since the environmental temperatures for fish are quite moderate. In Iceland, the largest is Kollafjord Experimental Fish Farm where salmon are raised to the smolt stage and either allowed to migrate to the sea from the farm or released in rivers. About 300,000 smolts are produced annually. Water for the hatching cabinets is kept at 12-14°C by indirect heating by geothermal water. However, one breeding station for salmon smolts uses warm spring water directly.

Utilizing heat from the geothermal springs, eels are bred in Hokkaido and Kagashima Prefectures in Japan. Eels bred in Ibusuki, Kagashima Prefecture meet 50% of the total demand. In Hokkaido Marine Hatching Center the profitability of breeding eels has also been found promising.

Here, geothermal water is mixed with river water and introduced to ponds where the temperature is kept at 23°C. Seed eels are brought in from elsewhere, propagated and the eggs hatched. Finally, the eels are shipped as adult eels of 100 to 150 grams each after breeding for one to three years [78].

In Japan, alligators and crocodiles of more than 20 species are bred in the hot geothermal water at temperatures of 28 to 30°C [103].

III. WORLDWIDE GEOTHERMAL RESEARCH AND DEVELOPMENTS

A. Major Developed Countries

Geothermal energy, with reference to achievements and practical experience demonstrated in various countries, holds out the promise of contributing to energy supply and economic growth, expecially in the less developed countries. However, scientific and technological research are essential to accelerate the use of geothermal energy in various fields of industrial and domestic life. Therefore, there is great need for much closer coordination of research activities and more efficient utilization of technical manpower active in geothermal energy research.

Recent investigations carried out in several countries have shown the possibility of utilizing geothermal energy in the near future much more widely and in different ways even with the present stage of technology.

The United Nations had long been interested in the development of geothermal energy, particularly in underdeveloped countires. In 1970, the U.N. sponsored the United Nations Symposium on the Development and Utilization of Geothermal Resources in Rome, where representatives of over sixty countries were on hand to discuss and present papers on geothermal energy and related fields.

Interest and enthusiasm within the engineering community for geothermal energy research is at a new high. Equally important is the continuing technological progress taking place in many areas of this field. An overview of where geothermal energy research and development stands in several areas and countries was seen at the Second United Nations Symposium on the Development and Use of Geothermal Resources, held in San Francisco, during the May 20 - 29, 1975 meeting. About 1,300 scientific, industrial, and governmental experts from 59 nations gathered to assess the current status of geothermal energy activities and where they are headed.

The following subchapters present data on present and future trends in geothermal resources research and development, which may range in scope from basic exploration to advanced commercial exploitation of geothermal resources.

Being subject to rapid cost changes, different exchange rates, and local financial capacity, the theoretical and actual costs for drilling of geothermal bores, production of geothermal power and heat are omitted in this study. Also, drilling and testing technology, equipment and instruments, and power plants equipment will not be outlined in detail for every country as they are rather standard, and as such are known to technical people in geothermal research and development.

1. El Salvador

In 1971, the National Electricity Agency (CEL) of El Salvador chose the LC-Electroconsult of Milan, Italy to design a 30 MW geothermal plant for construction of a geothermal power station at Ahuachapan. This marked the successful completion of a geothermal exploration program jointly sponsored by the government and the United Nations. Even before this program began in 1965, the National Geologic Service of El Salvador had explored the Ahuachapan fumarole area and drilled two shallow wells [10].

The Ahuachapan area is situated in the western part of El Salvador. There are two types of geothermal fluids: mixture of water and steam of acid character, and neutral, chlorine-rich thermal water. This area belongs to the central graben, which contains Quaternary volcanism. The zone including this field has considerable geothermal activity where over 40 separate sites are known. Prospecting drilling was done during the 1956 - 1958 period, and the deepest drilling reached about 400 m in depth.

Regarding geologic characteristics of the area based on drilling data, the steam is confined to fissure zones. The geothermal emanations occur in the Quaternary volcanism distributed in two belts 20 km apart. Most of the calorimetric studies have been conducted in the

volcanic belt of the south. The Ahuachapan structure has undergone displacement in the graben up to 1,000 m in the vertical direction, and faults originated at the end of the Pleistocene. The graben has a pyroclastic cover 300 to 500 m thick. The hydrothermal activity is located along the boundary lines of the graben as well as inside the graben. The steam is believed to originate in percolating water, fed by hot fluids travelling through fissures in the basement, principally in the region of volcanos of the Pleistocene. Drilling has shown that the steam is produced from fissures in the Pleistocene cover.

It has been estimated that the surface heat losses are 8×10^4 K cal/s, with an average heat flux of about 100×10^{-6} cal/sq cm/s, this fugure comparable with the normal heat flux in El Salvador, which is 2.5×10^{-6} cal/sq cm/s.

Sufficient heat to install a plant of 0.5 - 100 MW is expected. The steam produced is low pressure and wet [14].

The Ahuachapan region occupies some 30 km^2 on the northern slopes of a range of Quaternary andesitic volcanoes, and contains over a dozen areas of fumaroles, warm ground, and hot springs. The easternmost peak of the range, Izalco, is active. Geologic mapping and supsequent drilling suggest the presence of a caldera, largely buried by late- and post-volcanic debris. Fumaroles and other heat emissions at Ahuachapan are controlled by annular fractures forming the caldera wall and by northerly trending transverse fractures. The highest fumarole temperatures occur at the southern (uphill) end of the structure, and reach 125°C. No wells have been drilled in that area. Average well temperatures are about 225° to 230°, the maximum 235°, at depths of 600 to 900 m. However, geochemical indexes suggest a reservoir-equilibrium temperature approximately 10° to 20° higher. Several workers have thus speculated that the higher temperature fumaroles to the south may more closely correspond to the reservoir source.

Reservoir fluid is a sodium-chloride brine of about 10,000 ppm concentration. Some 15 percent flashes to steam in the wellbore.

Because average mass flow is about 320,000 kg/hr, it is expected that seven production wells will be needed for a 30 MW plant. No pressure declines have been noted in production tests. The disposal of saline reservoir fluid presents a problem, since boron, chloride, and arsenic are present in amounts potentially harmful to agriculture. In reinjection tests, a production well has been used for disposal into a deep, hot aquifer. These tests have continued for a year and a half without definite effects upon the adjacent production wells. The question of possible silica deposition in reinjection wells remains unanswered. The alternative to reinjection is disposal to the sea via holding ponds and the natural river drainage system.

A conservative estimate of developable potential at Ahuachapan is 100 MW for a 50-year period. Drilling to date has explored only 2 km^3 of an estimated 40 km^3 field volume. Exploratory drilling has also been carried out at Berlin, in the eastern part of the country. A well drilled in 1968 to nearly 1,500 m encountered temperatures of at least 225°. Flow of hot water was not sustainable, indicating restricted permeability. Another hole drilled to 600 m, 10 km to the northwest, flowed strongly and continuously at about 100°. Both wells exhibited moderate chloride salinity. Further exploration is warranted [10].

The Ahuachapan is a relatively large area of steaming ground and intense surface alteration, with large mud pots developed during the rainy season. The area is situated at an elevation of 750 m. Four exploratory holes were drilled to shallow depths in 1956. One of these was available for sampling during the present study. This drill hole is 220 feet deep and the maximum temperature recorded was 138°C.

The chemical data of surface hot springs and fumaroles, as well as drill hole discharges in the Ahuachapan area, give an indication of two fundamentally different water types: the hot spring waters representing a shallow layer of thermal water with a maximum temperature not exceeding 150°C but probably considerably lower, and the deep thermal

water of the drill hole discharges with high salinity and a temperature of 228°C but indications of higher temperature. From the available data it is suggested that a likely origin for the hot spring water is steam and conductive heating and slight admixture with the water of the deep reservoir. Isotopic analyses of the different water types suggest that the hot spring water and the deep reservoir water are of common meteoric origin.

With the presently available data on the chemistry of the deep reservoir water it is not possible to arrive at any definite interpretation regarding the origin of the dissolved solids [204].

Besides exploratory work in the Ahuachapan area, considerable prospecting is conducted in the El Tronador region, near the Tecapo volcano, and in the northeastern basin of the Torola river [162].

After completion of the first station of 30 MW capacity at Ahuachapan, the government is planning to build another power plant of 30 MW capacity, to reach total production of 60 MW capacity by 1980 [10].

In general, geothermal potentials of El Salvador seem to be economically promising. The geological setting of the existing thermal fields is not too complicated, making it possible to exploit geothermal steam at a reasonable cost. It is hoped that within the next decade the existence of enough steam will warrant construction of geothermal plants with a capacity up to 100 MW [210].

2. Iceland

Iceland has pioneered in the use of hot water for municipal heating starting in the 1920's. Approximately 50 percent of the 200,000 population receives geothermal heating, and will rise to over 60 percent in this decade. Nine out of ten homes in Reykjavik, the nation's capital, receive geothermal water for home heating, distributed by the Reykjavik Municipal District Heating Service. Low enthalpy hot water fields at Reykir and within Reykjavik supply this energy from reservoirs

at base temperatures of 98° and 146°C. Over 100 wells have been drilled on these fields, with deepest at 2,200m at Reykjavik. Another low enthalpy field is under development at Ellidaar, 3 km from Reykjavik. It is expected that this field will supply energy for expansion of geothermal heating in the Reykjavik area. Because the mineral content of the water is remarkably low from geothermal fields (less than 400 ppm average), no processing other than separation of contained gases is needed.

Space heating systems in operation or under construction elsewhere in Iceland will serve the needs of an additional 25,000 persons, mostly in small towns and villages on the southwest coast and in the north-central part of Iceland. Geothermal greenhouse operations in southwestern Iceland supply much of the fresh vegetables for the Reykjavik market. In addition, heated baths and pools are found all across the western and northern parts of the country.

At Namafjall, near Myvatn lake in northern Iceland, rich sublacustrine deposits of diatomite are dried with geothermal steam. Nearby a 2.5-MW (other source 3 MW) geothermal power has been in operation since 1969. Exploration began at Namafjall around 1947, in connection with attempts to mine sulfur from the fumarole field. Drilling revealed a high enthalpy hot water reservoir with a base temperature about 260°C and a maximum measured temperature of 286°C. Seven wells were drilled to an average depth of 700 m, and the deepest in excess of 1,380 m. Four of these wells are in operation, yielding 1.8 million kg/h of superheated water. Some 240,000 kg/h of steam separated from water is used to operate the power plant and diatomite plant. However, the water containing mostly sodium bicarbonate and silica is not strongly mineralized, and the gas content is similar to that at Larderello, Italy; some shallow wells have produced almost dry steam.

There is a pilot plant under way to dry seaweed with natural heat (water at 100°C) for recovery of alginates. A geothermal

brine with the approximate composition of seawater is under study for the recovery of various chemicals, including magnesia, table salt and bromine.

In the 1950's, when the present generation of nuclear reactors was in the design stage, the potential for recovery of heavy water, D_2O, by geothermal fluids was evaluated [10] . The dual temperature H_2S process for the production of heavy water depends upon the use of two countercurrent exchange towers. One is operated at low temperatures, the other at higher temperatures. Hydrogen sulphide is led up through both of these towers countercurrent to water. In the hot tower H_2S is capable of stripping the heavy water fraction away from the bulk of ordinary water, but in the cold tower the heavy isotope in the hydrogen sulphide is returned so that the water effluent from that tower is enriched by the heavy isotope. This process requires a great amount of steam for heating in spite of heat recovery by exchangers. For that r on the feasibility of this process was studied in Iceland in connection with geothermal heat.

Ordinary fresh water contains about 149 parts per million of the heavy hydrogen isotope. This concentration may, however, vary somewhat. It is of importance that the feed water to such a plant have a high concentration because the production cost will be about inversely proportional. Aside from that, such a plant could be built almost any place where there is cheap energy for themal and electrical purposes.

A plant of this type uses normally about 6 tons of steam for every kg of heavy water. According to the study of the Iceland Nuclear Science Commission, the economic advantage gained by the use of geothermal energy would of course depend upon the energy price levels taken for comparison, but referring to western European countries the advantage would be considerable.

<u>The conversion of bauxite to alumina.</u> Aluminum is ordinarily produced from alumina, which again is extracted from

bauxite ores. The bauxite is leached in a hot alkaline solution in the Bayer process, the product of the leaching filtered, and the pure aluminum hydrate crystallized out of the solution. Steam is required here both for the leaching and the recovery of caustic from the dilute alkaline solution coming from the crystallization process.

Natural steam could undoubtedly be used with some advantage here if the transportation of the bauxite to the steam field and the transportation of the alumina to the point of aluminum reduction would allow it. The question was studied in connection with the potential use of hydro power for reduction in Iceland, but in recent years there has been an obvious tendency to produce alumina close to the mines, whereas alumina is still being produced where there is a cheap source of electrical power [52].

The conditions for using noncondensing turbines in Iceland appear favorable as heat energy is cheap and abundant, and no advantage accrues from large plant size since a small population is distributed in villages and on farms across a large area. Therefore, multiple, small capacity plants appear to be the most effective scheme. This suggests a bright future for low cost geothermal electric power. The savings in fuel oil for heating purposes in the Reykjavik district amounts to some 200,000 tons per year. An additional 20,000 tons of fuel oil would be required for existing greenhouse operations. This is an appreciable savings for a small nation, considering that if this heating were done entirely by electricity, which is not the cheapest alternative, some 200,000 kw of generating capacity would be required for peak demand.

Four high temperature regions are known: three in the southwest and one in the north-central part of the country. Myvatn thermal region, in the north-central part, has a base temperature of approximately 280°C and constitutes an area of 50 km^2 and it includes

the Namafjall field. In southwest Iceland, aligned from southwest to northwest at intervals of 30 km, Reykjanes, Krysuvik, and Hengill have base temperatures of 280, 220 and 260°C respectively. Hengill, the largest, has an area of 70 km^2 and includes the important field of Hveragerdi at its southern end. At least eight deep and several shallow holes have been drilled in this area. The deepest hole at Hveragerdi is about 1,200 m and produces dilute superheated water. About 25 percent flashes as steam, and between 13 and 32 MW of electric power is planned. Reykjanes has had seven holes drilled to a maximum depth of 1,750 m. These wells yield brine with chloride concentration up to 29,000 ppm. This brine is considered to derive from seawater by steam separation in a thermal regime of 270°C. A system for recovery of various salts from the fluid, with concurrent generation of electricity, is under evaluation. At Krysuvik, about 30 km south of Reykjavik, plans have been made to transport superheated water to the capital for space heating in the event that growth of the system exceeds the capacity of the Reykir and Reykjavik (Laugarnes) fields. Here also, large flows of dilute superheated waters are obtained from more than a dozen wells as deep as 1200 m [10].

The Laugarnes field has been under exploitation since 1928 for district heating of the city of Reykjavik. Initially, production was from shallow artesian wells, but since 1962 has been wholly by pumping from deep wells. In general, the production of this field originates from three aquifers. Temperature in the upper aquifer, which is about 200 m below ground level is 110-120°C, in the central aquifer, the temperature is 135°C, and in the lower aquifer, about 2,200 m below ground level, 146°C. From 1957 to 1962, withdrawal rates were relatively uniform as the flow was mainly artesian. Since, 1962, following the introduction of deep well pumping, the flow has varied seasonally, the winter flow being about 3 times the summer flow. The winter peak draw-off is accompanied by a draw-down

in aquifer pressures which is almost entirely recovered during the summer. From January 1957 to August 1969, the net decline in pressure was equivalent to 66.8 m waterhead [13].

Besides space heating, a geothermal salt plant has been projected at Krysuvik, some 30 km south of Reykjavik. The projected capacity of the plant is 60,000 metric tons of salt annually. Sea water is to be piped over a distance of 7 km and concentrated in triple-effect vacuum evaporators. The concentrated brine flows to a settler where bicarbonates and calcium are precipitated. The salt is crystallized in double-effect equipment, dewatered, dried, compacted and briquetted. The evaporators are operated by natural steam at a pressure of 1.4 to 1.7 atm abs. The consumption of steam is about 16 units weight of steam per unit weight of salt. However, at Krysuvik, the processing of sea water for the production of gypsum and other materials dissolved in the sea was considered [8].

The brine which is obtained here is believed to be geothermally altered seawater, and appears to have a rather uniform composition when discharged at atmospheric pressure. The hot springs in the area and discharge from drillholes down to 300 m have suggested the composition given in Fig. 28, which represents an average of several analyses for most of the elements. The chloride concentration in the samples from the boreholes collected at 100°C is generally around 29,000 ppm. This value for the chloride corresponds to a ground temperature of 272°C if the original fluid is seawater of a chloride content of 19,000 ppm in a system of constant enthalpy. The highest temperature measured in drillhole is to date 286°C at a depth of 1166 meters.

Element	After flashing to 100°C ppm	Calcul. comp. before flashing ppm	Seawater ppm	Brine/seawater ratio at equal chloride concentrations
Cl	29,000	19,000	18,980	1.00
Na	14,900	9,760	10,556	0.92
Mg	24	16	1,272	0.013
S	24	16	884	0.018
Ca	2,500	1,638	400	4.1
K	2,070	1,355	380	3.6
Br	104	68	65	1.05
B	137	9	4.6	1.95
Si	(300)	(200)	0.02 -4.0	<(50)
F	0.8	0.5	1.3	0.4
Li	7.7	5	0.1	50
As	0.12	0.08	0.01 -0.02	< 4
Mn	0.05	0.03	0.001-0.01	< 4
Cu	0.00		0.001-0.01	
Zn	0.00		0.005	
Pb	0.00		0.004	

Fig. 28. The composition of the geothermal brine at Reykjanes compared with ordinary seawater [145].

These and other high temperature fields occupy the zones of crustal rifting and active volcanism in Iceland. Outward east and west from these zones are extensive sheets of Late Tertiary basalts through which abundant warm and hot springs issue. The high temperature reservoirs, however, are associated with the main Quaternary rift. Furthermore, many are closely associated with Late Quaternary centers of dacitic and rhyolitic volcanism rather than with plateau basalts. Significant associations of high enthalpy reservoirs and acidic volcanism occur at Myvatn, Askja, Geysir,

Hengill, and at least half a dozen other areas. Only in the zone from Reykjanes to Krysuvik, some 30 km long, the silicic volcanism is absent. Permeability within a reservoir may be controlled by lithology or by fractures. Thermal emissions to the surface are generally fracture-controlled.

Low temperature systems have been explored at several parts of the southwest, west, and northwest coasts of Iceland. At Hildardalur, 35 km southeast of Reykjavik, a hole drilled 1,500 m deep into an area of high temperature gradient failed to yield water. Temperature measurements of 150°C at 700 to 800 m indicated a potential reservoir formation. This formation was artificially fractured and induced to flow, representing perhaps the world's first stimulation of a geothermal system experiment. At more than a dozen localities in western and northern Iceland, hot water is produced from wells at temperatures between 90 and 180°C. These, which are not already in use, have potential for use in agriculture and space heating. In most cases, water quality is high, with one or two reported instances of geothermally heated seawater; less saline than that at Reykjanes. These lower enthalpy fields are almost exclusively associated with centers of basaltic volcanism.

Increase in consumption of hot water can be expected in Iceland, with an equivalent of over one-third million tons of fuel oil annually. However, electric power generation may increase slightly at Namafjall, and may begin at Hveragerdi in the Hengill area. Perhaps 15 to 35 MW capacity will be installed by 1980 [10].

Several new fields have been discovered, largely on the basis of shallow temperature gradient surveys. In the low temperature area (100-110°C), the Ellidaar field, close to the city

of Reykjavik, yielded 80 l/sec and its capacity is evaluated at 170 l/sec of water. The wells are about 1,000 m deep [127].

The hidden geothermal resources in Iceland have received considerable attention. The great amount of drilling that has been carried out in many thermal areas and the rather uniform geology of the country are helpful aspects. The main facts are that the flood basalts are permeable down to a depth of 2,000 to 3,000 meters and that the temperature at the bottom of the formation generally appears to be 100 to 150°C. Based on these assumptions, in 1962 the first experimental drilling was started at Akureyri to a depth between 1,500 and 2,000 m, in an area without surface manifestation [8] .

Exploration of thermal areas in Iceland is being carried out by geological, geophysical and geochemical methods as well as by drilling. The high temperature areas that have mainly been explored in recent years are the Reykjanes, Krysuvik, Hengill and Namafjall areas. These areas are favorably located with a view to their possible uses for heating and industrial utilization. Temperatures of about 280°C have been found in the Namafjall and Reykjanes areas, about 260°C in the Hengill area and about 220°C in the Krysuvik area.

Shallow drilling for temperature gradient measurements has been used with some success in low temperature areas. This method is of limited value in many of the high temperature areas because of disturbance of the temperature field by the cold shallow body of ground water. Surveys of microearthquake activity appear to offer promising possibilities, as this activity has been shown to be stronger in some of the high temperature areas than outside them [169] .

Magnetotelluric survey in sotuhwestern Iceland provided three basic characteristics of regional distribution of temperature gradients. Temperature gradient of deep wells (1 - 2 km)

ranges between 60 and 120°C/km and can be linearly extrapolated up to the base of the crust; between the crust and upper mantle (10 - 15 km) ranges from 1000 to ±200°C/km, and that of the upper mantle (15 - 1000 km) is essentially small - about 1°C/km [170].

In 1966 and 1968 aerial infrared surveys were conducted over 10 to 13 high temperature thermal areas in Iceland. The surveys were made with an airborne scanner system utilizing radiation in the 4.5 - 5.5 μm wavelength band. Supplementary ground geological studies were made in the Reykjanes and Torfajokull thermal areas to interpret features depicted on the infrared imagery and to relate zones of high heat flux to tectonic structure. In addition to their value in preliminary studies of high temperature areas, they can provide valuable data on changes that occur in surface manifestations with time [171].

The high down-hole temperatures discovered by drilling in the Namafjall field, and other evidence gathered during the exploration of the area indicated that a base temperature of perhaps 300°C might be expected. This encouraged a study of the possibilities of exploiting the field for additional geothermal power generation. The State Electricity Authority (now the National Energy Authority) in 1967, bearing in mind the results obtained in the Namafjall field, indicated that geothermal power station with atmospheric exhaust in the range of 5 - 10 MW each unit could be built, assuming a base temperature of at least 250 - 260°C. At an annual load factor of 8,000 hr/year (base load operation) the generating cost would be in the order of 4.5 - 5.5 US mills/kwh (1970). This would include the necessary boreholes, steam piping, and the power station itself [173].

Besides a 2.5 MW geothermal power station in the Namafjull area, northern Iceland, another geothermal station at nearby Krafla is under construction since 1974. This station, under

authority of the Krafla Project Executive Committee, will be equipped with two steam turbines (each 30 MW) manufactured by the Mitsubishi of Japan. This station will operate double pressure turbines utilizing steam flashed from hot water. The advanced cycle for full conversion of geothermal energy into electricity is shown in Fig. 29.

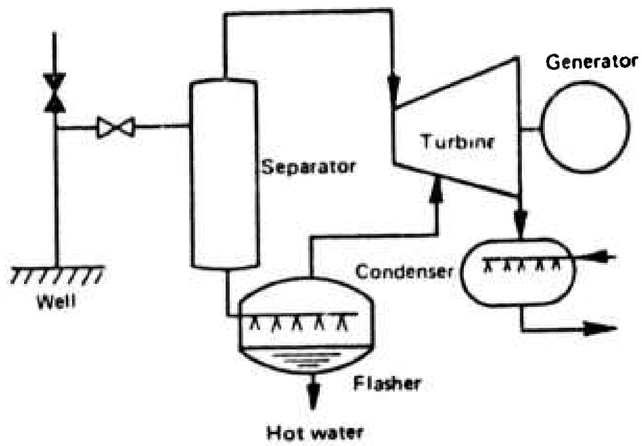


Fig. 29. Schematic of the energy cycle for Krafla geothermal power plant [172].

The hot water coming from the steam separator is flashed to generate steam, which is fed into the turbine at a suitable stage of the bladings, and results in the lower capital and operating costs per kw generating capacity. To enhance efficiency and economy of the initial and operating costs, Mitsubishi has developed a method of transporting mixture of steam and hot water for separation and flashing right at the turbine side. Naturally, separation and flashing may be done at the wellhead for transportation to the turbine. The merits of this cycle are: increase of power generation, lower generating cost per kw/h, decrease of hot water discharge, and less wetness of turbine exhaust steam [172, 180].

The pioneering work carried out in Iceland gives evidence that geothermal energy is a very common source of energy for domestic and industrial use, and experience in Iceland seems to have been assimilated by many countries.

3. Italy

At Larderello in Tuscany, the Italians have been extracting boric acid from steam jets ever since the 18th century and it was here that power was first successfully generated from geothermal heat. Even before the turn of the present century attempts were being made to use reciprocating engines supplied with raw natural steam. Great credit is due to the Italian engineers for pioneering the development of goethermal power and their enterprise has been a source of encouragement to others [2].

The current energy crisis has increased interest in geothermal energy, which is economic, domestic, and nonpolluting source of electric energy. The National Electric Energy Agency (ENEL), from the very beginning of its activity, has initiated a vast research program in the geothermal field, in strict collaboration with the Consiglio Nazionale delle Richerche (National Research Council). The National Research Council provided substantial financial support for the International Institute for Geothermal Research, Pisa, also sponsored by UNESCO. The Institute is devoted to the scientific and technological research on geothermics. The Institute with the support of ENEL has provided a laboratory in Larderello, where the first international postgraduate course in geothermics was organized in 1970. The CNR and ENEL undertook an intense program of research to enlarge the possibilities outside the geothermal basin of Larderello. The preliminary research was therefore concentrated in the Apennines Zone, which extends from Tuscany to Campania and which includes Colli Albani, Monti Sabatini, Monti Vulsini, Naples, Radicofani, Roccamonfina, Roccostrada, Travale-Radicondoli, and Viterbo-Monti Cimino. This program, 80 percent of which is already realized, has

permitted the selection of areas suitable for deep drilling. In some of these areas, industrially interesting results have already been obtained, resulting in the realization of a new output of approximately 250 million kwh annually, in addition to the discovery of various steam deposits.

ENEL's geothermal research program has not been limited to the above mentioned areas, but includes research in the areas of Vulture, southwest and southern Siciliy, central and southern Sardinia, and the smaller islands. Research in these areas is still in the initial stages and will expand in the future.

Italy's advance position in geothermal research and development was instrumental in providing valuable assistance abroad, such as the Azores, the Canary Islands, Chile, Colombia, El Salvador, Republic of China, Guatemala, Mexico and Turkey. Such activities are generally undertaken with consulting companies and in cooperation with Italian industries, which in the construction of geothermal plants acquired an experience and efficiency which ranks them among the leaders in geothermal research and developments.

The current state of energy crisis therefore finds ENEL involved in an increased acceleration of geothermal research, as well as in the much difficult field of exploration toward analyzing the possibility of drawing geothermal energy from the hot, dry rocks beneath the earth's crust.

Geothermal gradient and heat flow exploration have been carried out extensively for endogenous fluids. The prospecting was based on temperature measurements by platinium resistance thermometers and on thermal conductivity measurements. The latter was performed by the Von Herzen-Maxwell needle proble method on cores drilled from suitable depths. The isogradient and isoflow maps thus obtained indicate the values of which merely represent the stage of geothermal gradient and heat flow [175] .

Regional thermal surveys have been undertaken in Italy in which the geothermal gradient was measured in 30-meter prospect holes. The holes were drilled along lines perpendicular to structure, and at intervals ranging from 300 to 600 meters. Although a good correlation was found between high thermal gradients and the steam producing zones, this type of survey is considered to be of a more regional significance, and is comparable to gravity and aeromagnetic surveys, rather than being useful for locating specific production fissures.

Electric resistivity surveys, in conjunction with gravity surveys, have been very helpful in locating the major faults that bound the horst and graben structures characteristic of the Italian steam fields. The electrically resistant anhydrite and carbonate rocks, which contain the steam reservoirs, are overlain by an impermeable, conductive shale. The resistivity method is successful because the thickness of the shale cover is characteristic of each fault block so that the resistivity survey shows the position of the faults as well as the comparative thickness of the shale, and therefore, the depth to the reservoir rocks.

The electrical resistivity method is useful not only for determining geologic structure, but also to indicate the presence of a geothermally heated zone. It has been found in Italy that ground heated from 17°C to 150° C decreases in resistivity by a factor of 5 and if heated from 17°C to 280°C, its resistivity decreases by a factor of 9.

The first heat flow data in Italy were published in 1963, and in 1965 a tentative heat flow value under the Mont Blanc was published based on temperature measurements in the tunnel. They remained isolated events until 1970, and since then the geothermal research in Italy has become a systematic one by the works of several institutions, mainly by the Institute

of Geodesy and Geophysics at the university of Bary and the ENEL. Fig. 30 shows locations of the geothermal measurements in Italy.

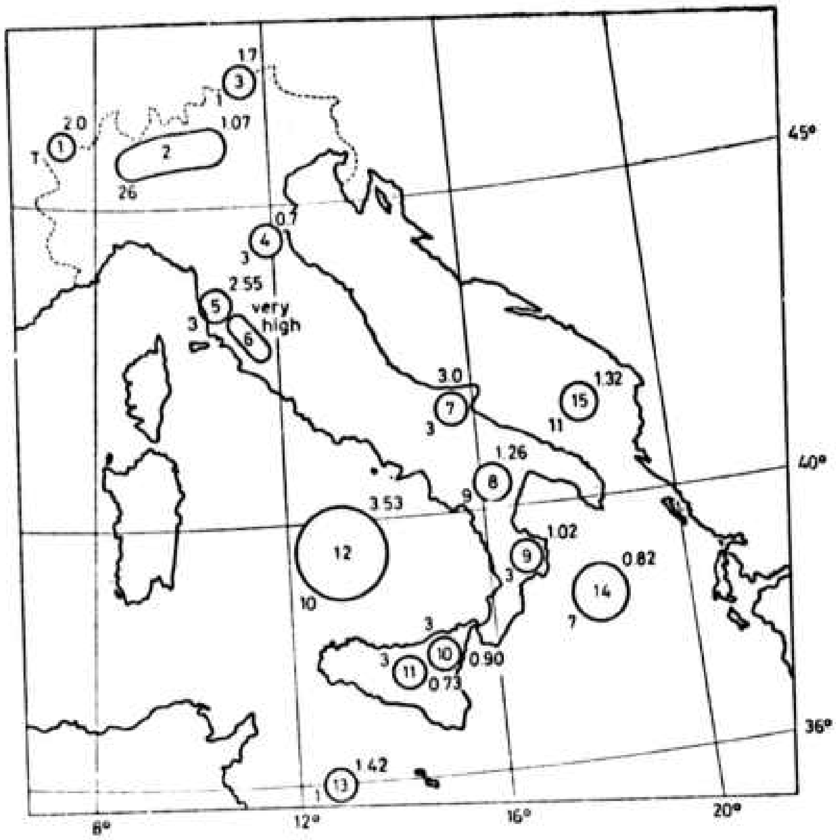


Figure 30. Location map of heat flow measurements in Italy [178].

Number in circle indicates the area: 1 - Mont Blanc; 2 - Northern Italian Lakes; 3 - Brenner; 4 - Romagna; 5 - Rosignano; 6 - Geothermal fields (Larderello, Monto Amiata and Monte Vulsini); 7 - Gargano headland; 8 - Fossa Bradanica (Bradano Trough); 9 - Calabria; 10 - Etna; 11 - Sicily; 12 - Tyrrhenian Sea; 13 - Sicily channel; 14 - Ionian Sea; 15 - Southern Adriatic Sea.

Numbers outside circle: (upper right) indicate the mean heat flow value in HFU; (low left) indicate the number of heat flow stations.

The numbers of the measurements are too small with respect to the complexity of the tectonic characteristics of Italian regions, and further measurements are necessary.

Figure 31 is a tentative map of the heat flow values of Italy and surround seas using observed and corrected values. The comparison between corrected (where available) and uncorrected values at least give qualitative information where their contrast is quite high. By this figure comparison, it seems that the Apennine chain divides the Italian peninsula into two geothermal areas: the western with high and eastern with low or normal heat flow [178].

Figure 31. Contour map of heat flow in Italy [178]. Low heat flow - less than 1.3 HFU; high heat flow - higher than 1.8 HUF.

Airborne thermal imagery survey of volcanic and thermal areas of Italy has been conducted with a Barnes T4 scanner with a crystal detector (aperture 1 millirad) sensible in the $8 \div 14\ \mu$ infrared range. Two atmospheric windows after and before the infrared opacity due to O_3 (10μ) were available. Besides the above scanner, Italians used E.M.I. Linescan which consists of an optical-mechanical system working in the across-track direction of flight. It is composed of a rotating, single-sided plane mirror set at 45^o to the axis of rotation which passes through the center of the mirror. Infrared imagery, like other geophysical methods, are used at the same time for several applications related to the geophysical field, as lithology, minerals detection, engineering geology and geothermal power [174].

The following are briefs of general geological features of major geothermal regions of Italy:

Larderello is 17 km south of Volterra. Natural steam vents were known before 1777, but it was then that the presence of boric acid was discovered. Count Francesco de Larderel was the founder of the borax industry and the region is named in his honor. Other localities in the neighborhood of Larderello are Serrazzano, Lagoni Rossi, Lago, Monterotondo, Sasso and Castelnuovo, all in Tuscany. The Larderello region covers about 400 km^2 with maximum elevation of about 1,000 meters.

Its structural geology is composed of impermeable Oligocene-Miocene strata (schistous clays) which discordantly overlies a permeable anhydrite series of the Rhaetic in which the steam occurs. The fractures emerge through the crystalline basement, and the steam is probably connected with a colling intrusive body severl kilometers below the anhydrate series.

In this region the first geothermal power station producing 40 hp with natural steam was installed in 1905. The average depth of the wells in this region ranges between 700 and 1,600 m. A total of 160 wells yielded 2,850,000 kg/h of steam (1964), at an average temperature of 200°C and an average pressure of 5 atm abs (14).

This region, often termed the Boraciferous region on account of the boron in its thermal waters and steam. The region is hilly and on account of its abundant mineral deposits (sulfides, oxides and carbonates of iron, copper, lead, zinc and other metals) it is called Metalliferous Hills. These deposits are in all probability associated with magmatic phenomena of relatively recent age in Tuscany, and should thus be correlated with the endogenous fluids of the region.

The first prospectors were guided exclusively by the numerous natural steam and gas jets, which very frequently caused violent ebullition in the natural basins known locally as "lagoni" [176].

In general, steam utilized at Larderello originates in the Triassic limestones protected by an impermeable cover of clays. These limestones, which are at the same temperature as the fluid they contain (200 - 240°C), constitute a heat source providing a considerable increment to the heat flux in the argillaceous cover, and cause a considerable increase of the geothermal gradient. Measurements of the temperature gradient have been made on a perpendicular profile in the producing zone in boreholes some 30 m deep. The time required after penetration of the drill for the borehole to attain thermal equilibrium has been determined by numerous experiments, and the limiting depth at which the variation of the surface temperature no longer affect the measurements has also been determined.

For a given heat flux, the temperature gradient varies with the thermal conducitivity of the formations, which is higher for limestones than for clays. A correction factor was therefore applied to each borehole to refer all the gradients to an argillaceous formation of low thermal conducitivity.

The curve of corrected temperature gradients shows high values in the central part of the profile, corresponding to a hot and structurally high zone, and lower values outside this zone.

To allow for the variations in the depth of the limestones, a curve of theoretical gradients was plotted under the assumption that the cover was homogeneous and that the surface of the ground and that of the limestones were both isotherms.

The mean conducitivity of the cover being higher than that of the argillaceous reference formation, the measured and corrected gradient should be higher than the theoretical gradient, because the limestones contain a superheated fluid.

This has been observed in the central part of the profile, which corresponds to steam production, but not in the nonproducing extreme zones. Geothermal prospecting thus permits sufficiently accurate localization of the zones where the conditions favor the presence of superheated fluid.

The presence of this fluid may, on the other hand, be related to anomalous high regional gradient. The test borings at Larderello were in the zone of influence of this gradient.

It would seem desirable to make sure of the actual existence of such an anomalous regional gradient in newly developed zones before undertaking detailed exploration and drilling. In the affirmative case, and only in that case, should the more detailed phase be entered by combining geothermal prospecting with classical geophysical methods to determine the zones most favorable for study [177].

Monte Amiata, 70 km southeast from Larderello, is situated in the provinces of Siena and Grosseto, Tuscany. As at Larderello, here the schistous clays are directly in contact with the underly anhydrite series which contain the steam. However, the sedimentary deposits are still affected by volcano-plutonic ignimbrites. The surface temperatures of the geothermal springs range from 20 to 50°C. Drilling has reached 400 to 1, 1000 m depth. A total of 12 wells have been drilled, and 5 of them produce 1,000 kg/h of a fluid containing 30% of gas at a pressure of 5.5 atm abs and a temperature of 150°C (14).

One substantial difference from the Lardrello region, however, is the presence of volcanic formations represented by ignimbrites which make up the relief of Monte Amiata from the level of about 800 m to the summit. These ignimbrites were produced by acid volcamism and their mass also contains true lavas in the shape of domes and extrusion ridges formed along the fissures through which the magma was ejected. The tectonics of the Monte Amiata zone likewise partially repeats the theme dominated at Larderello. At many points the stratigraphic sequence is reduced and stratified, putting the schistose clays into direct contact with the anhydrite series. A further complication, however, has been introduced by the magmatic intrusion, followed later by a sharp volcano-tectonic collapse due to the eruption, and which has given rise to a new fault system.

In this region, near the volcanic shield, a series of modest manifestations are noted. They consist of hot springs, ranging in temperature from 20 to 50^{0}C, and mainly of cold gas vents composed essentially of CO_2 and H_2S, aligned along the principal fissure systems. This activity, which is very modest, owing to the high impermeability of the argillaceous cover, distinctly differentiates the Amiata zone from the classical zone of Larderello.

In this region a series of preliminary surveys and exploration work have been carried out which comprised a geo-tectonic detail survey consisting of anaylses and studies relative to the problem, and geophysical exploration by the resistivity and gravimetric methods.

Besides the regions described above, there are also other regions where important preliminary prospecting work has been undertaken to determine the possibilities of discovering endogenous fluids that can be industrailly exploited.

Owing precisely to the preliminary status of these operations, it does not seem advisable to describe in detail the characteristics of each region. Since they are, incidentally, very similar to each other, only the common features of the geological and hyrothermal will be mentioned. [176].

Roccastrada, located 30 km southeast of Larderello in the provinces of Siena and Grosseto, Tuscany is in the stage of exploration and investigation. The structural geology of this region is probably similar to that of Monte Amiata. The average surface temperature of geothermal springs is around 55^{o}C (14).

Montecatini-Orciatico region is 25 km north of Larderello, in the province of Pisa. This region is in exploration and investigation stage. The structural geology is similar to that of Monte Amiata. Preliminary drilling commenced in 1964. The surface temperatures of the thermal springs are about 55°C.

La Tolfa region is a few kilometers from the Tyrrhenian coast, in the province of Rome. In 1964 it was in the exploration state. (14).

The features common to Roccostrada, Montecatini-Orciatico and La Tolfa are the existence of a series of sedimentary formations similar to that of Larderello, with very impermeable horizons covering deep formations, more or less permeable, and mainly the presence of recent volcanic acid products (ignimbrites), similar to, and perhaps contempary with those of Monte Amiata.

The tectonics is marked by structures strongly uplifted over the others, and by lines of faults of varied orientation [176].

Monti Berici region is located in the province of Vicenza, Venetia. In 1964 it was in the exploration stage. The trap in which the steam has been accumulated is probably formed of recent rocks of volcanic origin.

In view of the general geologic situation in the Italian geothermal field which are unique in their characteristics, there are considerable speculations as to whether the steam is endogenous or exogenous, i.e., whether it comes from magmatic fluids or is formed primarily by meteoric water. However, it is of major importance in a region of thermal

manifestation to have sufficient bases to be able to consider a favorable geological trap structure. This is a practical consideration that is borne in mind during exploration in a steam field, and may perhaps be responsible for drilling in some parts of Italy where there are no superficial manifestations. After all, if the heat is at least partially associated with intrusive bodies at a certain depth, it is important to know the existence of successive permeable and impermeable formations capable of forming geologically favorable traps, in order to constitute deposits of heat. The fluids themselves may result either from deep magmatic influence or from shallow meteoric influence. It may be unnecessary to devote practical consideration to the trap, provided an adequate idea of the structural geometry of the formations in depth is obtained. Detailed geological reconnaissance, in addition to gravimetric, electrical and seismic exploration, is recommended in advance of any drilling. Hydrogeological studies are supplementary tools, and isotope geology and geochemistry play the important part of being concerned with the origin and evolution of the elements in the fluids [14] .

In the following is a condensed outline of geothermal power production and exploration in Italy.

From the simple 250 kw generator of 1913, the Italian geothermal generating complex has grown to over 390 MW capacity, and is currently the world's largest. (The original boric acid recovery works, established in 1812, was shut down in 1969 because of inability to compete economically with other sources of borax.) Over 365 MW of the electrical capacity is produced from the thirteen plants comprising the Larderello field. Some 25 MW are supplied by the four plants at Monte Amiata, 75 km to the southeast. Individual turbine size is small, ranging from the 900 kw noncondensing unit at San Ippolito to the 26,000 kw plants at Castelnuovo and Larderello.

Approximately 43,000 kw are generated from a series of noncondensing turbines at the Larderello and Monte Amiata fields. Noncondensing turbines were chosen originally because of their simplicity, lower capital cost, and ease of construction. However, they consume approximately twice as much steam per kwh as condensing turbines, 20 kg vs. 10 kg. In a situation where steam is abundant, capital scarce, and time short, noncondensing turbines appear to be most favorable. But with the expansion of the Larderello complex to the point where many geologists believe that field capacity has been reached, or nearly so, effective utilization of steam becomes the more critical variable. For this reason, conversion to condensing turbogenerators is planned. This could add upwards of 40,000 kw of generating capacity at Monte Amiata and Larderello without any increase in steam production.

Producing pools of the Larderello field are at Capriola, Castelnuovo, Gabbro, Lago, Lagoni Rossi, Larderello, Montecerboli, Monterotondo, San Ippolito, Sasso Pisano, and Serrazzano. From Monterotondo on the south to the northern end of the field at Gabbro is a distance of some 20 km. Total field area is probably in excess of 250 km^2. In addition, steam has been discovered at Travale, Boceheggiano, and Roccastrada, east and southeast of the main Larderello field. Roccastrada is nearly halfway between the center of the Larderello field and the Bagnore and Piancastagnaio pools of the Monte Amiata field. Radicofani may represent an eastern extension of the Monte Amiata field.

Approximately 500 wells have been drilled across the Larderello and Monte Amiata fields, of which nearly 200 were in production in 1971. The reservoir fluid is steam, with a variable content of noncondensable gases, averaging about 5 percent, although the initial gas content of each well is much higher, e.g., the gas content at Piancastagnaio had decreased from almost 90 percent initially to 20 percent by 1970, and was still decreasing. Reservoir temperatures reach a maximum of about 250°C.

Average well yield is about 23,000 kg/hr of steam at Larderello and perhaps 36,000 at Monte Amiata. The greater average yield at Monte Amiata reflects the shorter production history, as both mass and pressure declines are reported with time. Individual wells may deviate greatly from these averages: mass flows as large as 270,000 kg/hr have been reported. Average well depth at Larderello is slightly over 1,000m. Wells are completed with 34 cm diameter casing, which is the largest production diameter at any active geothermal development in the world.

There is evidence of interference between wells in certain pools, and it is reported that maximum sustainable mass flow has been attained for several parts of the field. This is reflected in the low average yield per well, which in turn reflects declines in yield per well with time. Many geologists have thus been led to state that field capacity has been reached. However, successful exploration and development is continuing at the previous margins of the field, most notably at Travale, where, beginning in 1951 with the drilling of five successful steam wells, a geothermal field was developed at the site of an old boric acid works. Two 3,500 kw turbines were installed in 1952 and operated until 1962, when decreases in well yeild required the plant be dismantled. In February 1972 it was reported that several new wells had been completed, and that they were capable of producing at least 100,000 kg/hr each of dry steam. This may significantly extend field capacity.

A series of seven target areas has been chosen for further geothermal exploration in the Apennine mountain chain. South from Monte Amiata these are: Monte Volsini; Monte Cimini, including the Viterbo area; Monte Sabatini; Colli Albani, to the southeast of Rome; the region about Naples, including Pozzuoli and the Campi Flegri solfatara fields of classical fame; and Monte Vulture, in south-central Italy. Other areas in northern Italy have been investigated and rejected.

These include Monte Berici, near Padua, where there are Late Tertiary silicic volcanic rocks, and Montecatini, between Larderello and Pisa. Drilling has also been done at La Tolfa, a volcanic center southwest of Viterbo.

In the 1920s and 30s, drilling was carried out on the island of Ischia and in the vicinity of the city of Pozzuoli. Low pressure steam was reported from certain of these tests. A project to study the feasibility of using a freon-based heat exchanger to generate electricity at the Campi Flegri was never carried through [10].

In the following table are data on geothermal power production of two major regions of Italy: Larderello and Monte Amiata [179, 181].

Region and Plant	Number of Units	Installed Capacity MW Unit	Installed Capacity MW Total	Net Production December 1969 (10^6 kwh)
<u>Larderello Region</u>				
Larderello 2	4 1	14.5 11.0	69.0	423.6
Larderello 3	3 1 2	26.0 24.0 9.0	120.0	757.6
Gabbro	1	15.0	15.0	71.8
Castelnuovo	1 2 1	26.0 11.0 2.0	50.0	262.3
Serrazzano	2 2	12.5 3.5	32.0	269.7
Lago 2	1 1 1	14.5 12.5 6.5	33.5	261.5

Sasso Pisano 1	2	3.5	7.0	5.3
Sasso Pisano 2	1 1	12.5 3.2	15.7	163.6
Monterotondo	1	12.5	12.5	108.3
Capriola	1	3.0	3.0	n.a.
Lagoni Rossi 1	1	3.5	3.5	23.1
Lagoni Rossi 2	1	3.0	3.0	9.9
S. Ippolito	1	0.9	0.9	2.8
TOTAL:	32		365.1	2,359.5
Monte Amiata Region				
Bagnore 1	1	3.5	3.5	13.1
Bagnore 2	1	3.5	3.5	18.0
Senna	1	3.5	3.5	32.0
Trvale	1	15.0	15.0	------
Piancastagnaio	1	15.0	15.0	112.7
TOTAL:	5		40.5	175.8

The total increase of fluid produced in recent years in the Larderello and Monte Amiata areas have been achieved only with difficulty, due to the fact that the limits of potentiality of the production features has been reached. Therefore, any future increase in geothemal power production is closely linked to the discovery of new primary energy sources.

An extensive exploratory program is under way in the following regions: Viterbo-Monte Cimino, Monti Vulsini, Roccamonfina, Naples. Detailed isotopic investigations have been carried out in different geothermal areas, as well as other geochemical investigations.

Geochemical and volcanological detailed investigations have been carried out in the Pozzuoli area. Its geothermal possibilities, already known by wells drilled some decades ago, seem to be very promising [127].

Regarding the potential for geothermal energy development by 1980 at Larderello and Monte Amiata, increases in power generation are likely to depend upon conversion from noncondensing to condensing turbines. This may increase capacity by 15 percent over the decade. But only if significant discoveries of steam are made at Travale, Roccastrada or Radicofani, there is likely to be new construction in the steam fields of Tuscany. If exploration elsewhere in Italy is successful, new generating facilities could be on line by 1980 [10].

4. Japan

Geothermal research and development in Japan began in 1919 at Beppu on Kyushu island, where one kw of electricity was generated by 1924. Somewhat earlier, the first heothermal heating of greenhouses began. The Tone Boring Company had begun a drilling program in several areas. At Yunosawa, on the south-central coast of Honshu, geothermal steam was used in a demonstration plant to generate 8 KW in 1948. However, it was not until the end of World War II, with Japan's industrial base in ruins, that serious geothermal research and development began. The Agency of Industrial Science and Technology, including the Geological Survey, several private electric drilling and mining companies, and prefectural governments,

independently and jointly began exploration of Japan's geothermal resources [10] .

The Japanese Geothermal Energy Association was established in 1960 for promoting scientific and technological development of geothermal resources, with the numerous organizations, technical experts, scientifical researchers and other related organizations deeply interested in this problem. Among several investigation committees within the association, the Geothermal Energy Utilization Committee (12 members) was engaged in clarifying the actual status of geothermal use in Japan and abroad. In 1968, this Committee made a particular study of geothermal energy use in the Otake area, Oida Prefecture [103] .

At Beppu, experimentation resulted in the generation of 30 kw electric power station in 1951. At Hakone, on the south coast of central Honshu, 30 kw of electricity has been generated since 1960 from steam produced in a shallow well. Other experimental generation of electricity has taken place on Hokkaido Island (Atagawa) and in the northern Honshu (Narugo).

Japan's hot springs have been used for therapy and recreation for centuries. Japan probably leads the world in the use of natural hot water in baths, therapeutic spas, and resorts.

Space heating systems, however, have not been as widely developed as in Iceland or the Soviet Union. Four district heating systems have been in operation in 1969 using hot water (not greater than $70^{o}C$) equivalent to about 5,000 tons of fuel oil annually.

Greenhouse heating with geothermal waters is common on farms and experimental agricultural stations, chiefly in south-central Honshu. Some are near Beppu, and a few are in the Shikabe geothermal area of Hokkaido Island. Commonly, garden vegetables, tropical fruits, and other plants are cultivated. At least two farms raise

chickens; at one pond eels and carps are raised for consumption, and at another aligators for industrial use.

There are several more specialized industrial applications. One, on Kyushu Island, involves the recovery of sulfur fr m deposits at fumaroles. At Beppu, 98°C water is used to process about 30 tons of rice annually for use by a bakery. In the Shikabe area on Hokkaido, salt is recovered from sea water by evaporation, using geothermal hot water and steam from a 70 m deep well. Though the operation produces only 150 tons of salt per year, a combined geothermal power plant and salt recovery works planned at Shikabe could produce 7,000 kw of electricity, up to 100,000 tons of salt annually, and some amount of fresh water. The proposed plant would use multi-stage vacuum distillation.

Exploration began in 1952 at Matsukawa, in northern Honshu, with the drilling of wells for steam to supply bathhouses. Japan Metals and Chemicals Company became active in exploration there in 1956, and was joined in 1958 by the Geological Survey and later by other organizations. At least nineteen wells have been drilled since 1952. Of these, six are classed as production wells, having an average depth of about 1,200 m. Five wells used for power generation yield an average of 110,000 kg/hr of dry steam. Two wells yield both steam and water in the ratio of about 4:1. Reservoir temperature, about 240° to 250°C, is much like that at The Geysers, California. The reservir formation is a fractured series of welded dacite tuffs and lavas of probable Pliocene age. These overlie Miocene sands and shales, Lower Tertiary "green tuffs," and Paleozoic slate and chert. Above the reservoir rocks are Quaternary andesites and constructional debris of very youthful volcanos.

Construction of the Matsukawa power plant began in 1961. Initial operation was at 9,000 kw. The facility has been expanded to 20,000 kw, with future expansion to at least 60 MW. Noncondensable gases,

which average about 0.5 percent, are expelled to the air. Condensate from the condensing turbine is discharged to the natural drainage, without known harmful effect.

Exploration begun in 1953 at Otake, on Kyushu Island, culminated in 1967 with the completion of a 13,000 kw power station by a group headed by Kyushu Electric Power, Inc. Ten wells were drilled at Otake, and two at Hachobaru to the south; five are connected to the condensing turbine. One well produces about 37,000 kg/hr of dry steam; the others produce larger amounts (up to 540,000 kg/hr of dry steam and water, with steam making up 10 to 25 percent of flow. Noncondensable gases total less than 0.5 percent of the steam by weight. The reservoir fluid is of sodium-chloride composition, but relatively dilute, averaging about 4,000 ppm. Maximum reservoir temperature is about 200°C. Maximum well depth at Otake is 900 m; at Hachobaru, one well is 785 m deep.

The geology consists of Pleistocene andesite lava and tuff-breccia, and occasional pumice beds, overlaid by Holocene sediments and volcanic ash. Structure is largely obscured by the constructional features of Quaternary volcanos. However, faulting is believed to be significant, forming down-dropped blocks. Hydrothermal alteration and thermal emissions are intense and widespread, suggesting fracture permeability to the surface. The wide range of flow rate and steam percentage from well to well suggests that permeability and stored fluid are limited in portions of the field. But no deep wells have been drilled, and the main reservoir may not yet have been encountered.

The Otake field is located in Aso National Park, thus requiring special permission for construction of plant facilities. To avoid pollution of natural steams, water discharges are pumped to a nearby hydroelectric reservoir. Limited life is predicted for the present wells because of scaling and fluctuations in pressure. Silica deposition in the discharge pipeline caused a restriction of power production in 1968 and 1969. Studies are still under way to control scaling. Calcium-carbonate scale, requiring acidizing, has been found in at least one well.

Despite these problems, additional wells are planned and production is to increase to perhaps 180 MW over the next decade or so.

At least 23 areas have been explored by drilling. Several are being evaluated for development, the most significant being at Shikabe, on Hokkaido Island; at several places near Matsukawa; at Onikobe, south of Matsukawa; and at Takenoyu and Hachobaru, near Otake.

In the Hachimantai volcanic area, northwest of Matsukawa, extensive geophysical work culminated in the drilling of at least nine holes to average depths of about 750 m. Temperatures reached 200°C at the south end of the drilled area, where hot water was encountered with up to 30 percent steam fraction. Exploration is continuing there, and the construction of a 10 MW power plant is being considered. The geology at Takinokami, southwest of Matsukawa, is similar. Temperature survey to 50 m (maximum temperature, about 200°) were followed by a 400 m well, which produced a steam and water mixture.

Onikobe has been the scene of exploration since 1962. It is a structural basin of about 60 km^2, in which there are numeraous fumaroles and hot springs. Exploration has included geologic mapping, geophysical surveys, and test drilling. On the basis of ten holes, with maximum depth over 700 m, and temperatures to 190°, drilling of production wells is under way. One hole is reported to produce nearly 30,000 kg/hr of superheated steam.

Takenoyu has been investigated since the early 1950s. Two wells were drilled to about 250 m in 1962. Bottom-hole temperatures were approximately 200°C. One well ceased to produce after a short period, indicating limited permeability in the reservoir. The other, however, continues to yield 3,000 kg/hr of saturated steam.

Geothermal exploration has been carried out also at Kucharo and Showa-shinzan volcanic centers on Hokkaido Island; Nasu in central Honshu; Hakone and Atagawa, on the south coast of Honshu; Oshirakawa, in west-central Honshu; and several places in the south of Kyushu Island. Many of the drill holes were to shallow depths, and exploration cannot be considered conclusive at most locations. High temperature reservoirs were located at Nasu (194°C) and on southern Kyushu Island (over 170°C).

A relationship has been noted between high temperature reservoirs and dacitic or dacitic-rhyolitic-andesitic volcanism in Japan. This observation is similar to findings in Iceland, New Zealand, the United States, and elsewhere. The Japanese fields, however, have not been marked by the high temperatures encountered at centers of silicic volcanism in New Zealand or Iceland. Well flow has varied widely, and probably reflects fracture rather than intergranular permeability in most Japanese fields. However, restricted permeability may represent a constraint upon development, but in power-short Japan, exploration is being pursued vigorously on all fronts [10].

The preceeding material is a brief chronologic review of general characteristics, geothermal research, and various developments in Japan. In the following are more detailed data on specific subjects and activities of major plants and fields arranged according to the table of contents.

The role of geology. - There are very many geothermal areas in Japna, most of them develop in Quaternary volcanic zones and in Tertiary volcanic districts. Hot springs and fumarolic fields occurring around Quaternary volcanoes are derived from andesitic or dacitic volcanism. Mostly dacitic and andesitic lava domes or volcanic spines fill the crater vents, preventing free discharge of volcanic energy from volcanoes, resulting in the formation of geothermal areas around them.

Some hot springs welling up through Tertiary sedimentary and volcanic rocks are closely related to the intrusion of acidic rocks such as rhyolite and quartz porphyry. Acidic magma rich in silica is more viscous than basic magma. Accordingly rhyolite, quartz prophyry or dacite intrusive masses often extend down to depth and permit heat accompanying gas or hydrothermal solution to rise from depth.

Though very few hot springs are present in pre-Tertiary rock districts, if compared with those in Quaternary and Tertiary rock zones, some of them are considered to be genetically related to granite.

The occurrence of geothermal fields in Japan seems to indicate that andesitic and dacitic volcanism in Quaternary and acidic intrusives in Tertiary rock areas often contribute to the generation of geothermal fields. This fact suggests that petrological considerations are very significant in the study of geothermal areas in Japan.

The most abundant hot springs in Japan are along Quaternary volcanic zones, and their heat sources are of course considered as existing within the young volcanoes themselves. But not all young volcanoes are always accompanied by hot springs. Very few hot springs exist on the basaltic volcanoes. For example Oshima, Miyakeshima and Fuji basaltic volcanoes have no high temperature hot springs. They often erupt and sometimes cause the formation of lava lakes. The lavas of such basaltic volcanoes are very fluid and their magmas are apt to sink again to magma reservoirs from craters and crater vents, after the activity has ceased. There is a break between the upper lava masses and the lower lava masses or magma reservoirs. Such geological conditions may not be favorable for the formation of hot springs or geothermal fields on the earth's surface.

Many geothermal fields are distributed around the volcanoes consisting of andesite, dacite and rhyolite. There are many hot springs in Japnn which are very rich in young andestic volcanoes. Valuable

geothermal fields develop in New Zealand where young rhyolite volcanoes are plentiful. Quaternary rhyolitic volcanoes are small in number in Japan, but they are accompanied by hot springs, like, for example, Shikine (72°C) on the Shikine, and Setoyama (62°C) on the Nii-jima volcanic island. These facts indicate that geothermal fields are generated by the young volcanoes consisting of acid (felsic) to intermediate (mafelsic) volcanic rocks, far more than by the basaltic volcanoes.

Hot springs are widely distributed in Japan in young volcanic zones of andesitic and dacitic lavas. Lava domes, volcanic spines and cryptodomes mostly have geothermal fields around them.

Dacitic lava domes seem to be more effective for the generationof geothermal areas than andesitic ones. Noboribetsu hot spring which is famous for its very high heat energy of more than 200×10^7 cal/min, is found near the Hiyoriyama dacitic volcanic spine. The Kawayu hot springs, the thermal water of which is well-known in Japan for its very low hydrogen exponent (pH 1-1.5) are genetically related to the Atosanupuri dacitic lava dome. Many hot springs are active around dacitic and andesitic lava domes in Japan.

The volcanic rocks which build lava domes and volcanic spines are mostly derived from acidic viscous magma. Such magma often plugs a crater vent and prevents heat and gas accumulated at depth from escaping into air. The volcanic rock body solidified from viscous magma sometimes extends down to depth. Such geological conditions may favor the formation of geothermal areas around lava domes. Some of the volcanoes formed during the Quaternary which dates back only 1,500,000 or 3,500,000 years at the most from the present, are considered as being able to retain their heat energy regardless of the existence or nonexistence of the above mentioned structure and mechanism. It has been estimated the life duration of

a volcanic hot spring which is a combination of two sorts of hot springs, of meteoric water origin and magmatic water origin, as being several hundreds of thousand to 2 million years, on the assumption that a magma reservoir at a depth of 5 - 10 km has a cylindrical form with a radius of 5 - 10 km and a thickness of 5 - 15 km.

There may, however, be various types of magma intrusion depending on their chemical compositions. It suggests that structure of magma intrusion is significantly related to the formation of the hot spring [183].

Methods of prospecting. In the early days of postwar development, bore holes were simply drilled in places near natural fumaroles in steaming ground. Many such wells produced steam jets rather easily, but were not satisfactory for fruther exploration. Conventional geological mapping, chemical analysis of hot springs, surface temperature surveys, detection of gases and radioactivity contained in the soil, and horizontal electric prospecting were the most common research methods employed before drilling, but these methods dealt only with the superficial feature of the terrain and told little of the underground characteristics. The importance of studying geological structure in depth was, however, soon realized. Since then, geological mapping has been devoted to clarifying detailed structural features, including stratigraphic successions, folds, faults, joints, rock features such as density, porosity and permeability, and hydrothermal alteration. Seismic, gravity and vertical electric prospecting to suit the geothermal areas has been devised and applied according to the characteristics of the fields. During the well drilling, not only core and temperature logging, but also electric logging was used to determine rock characteristics. The physical and chemical characteristics of steam discharged from the wells have also been measured at most places [184].

Heat flow measurement. There are many hot springs and geothermal phenomena owing to post-volcanic activity in Japan, and there are some wells in these places, from which the near surface temperature distributions can be measured. In such places, the value of heat flow consists of that derived not only from the usual thermal conduction, but also from the heat transportation by liquid, steam or gas. And the temperature curves show a steep slope in the shallow part and then those sloopes become gentle. Generally speaking, in Japan, in the case of the shallow part, the heat flow is 30-40 HFU and in the deep part this is 4-5 HFU and the average becomes 12-13 HFU.

These values seem to be rather lower than expected; however, taking note of the heat flow into the well through the well wall from the surrounding rocks after the completion of the well and, considering furthermore the outward heat flow through the outlet of the well after the start of the steam jet, the picture completely changes. For example, in the case of Matsukawa, these values become 2.3×10^3 HFU before, and 3×10^9 HFU after, respectively. Such large amounts can only be obtained in the case of concentration of outward heat flow through the well.

Now, let us consider the penetration speed of hot water into the well from the area's rock formation. This is 5×10^{-2} cm/sec. On the other hand, the permeability of rock core sample shows 10^{-9} to 10^{-5} cm/sec. This may indicate that the major part of the liquid which has entered the well through the well surface has been through fissures or cracks [185].

Seismic exploration. During the last several years, seismic prospectings have been conducted in some geothermal fields (Matsukawa,

Otake and Onikobe) in Japan. In Japan, all of the geothermal fields are in volcanic areas, consequently mostly reflection techniques and partly refraction ones have been applied because of the complicated velocity distributions in such geothermal fields. From these field data, some interesting information has been obtained, however, it is rather difficult to distinguish the feature of cap rock, hot fluid reservoir and fault structures and to get deeper information related to heat sources from these complicated data.

From such view points, recently, two techniques have been tried, the first one is to remove the undesirable noises and multiple reflections to be able to make clear the deeper structure, by using digital data processing including the newly established software. The second one is to use not only the conventional arrival times, but also to utilize the absorption of wave energy caused by the fluid viscosity and high frequency, and to study the wavelength of a seismic wave to presume the geophysical state in such geothermal fields.

From the first one, in some geothermal fields, a very interesting deeper structure (about four kilometers' depth) which may indicate the structure related to the heat source, has been obtained, and from the latter, it has become clear that the areas where low frequency wave patterns predominate, correspond to the fluid reservoir. By comparing these seismic data with the related geological, geophysical and geochemical data, the application of a seismic method will be surely increased not only to find the suitable area for the utilization of natural steam from volcanic areas for electric power generation, but also to know the underground geothermal characters of those areas [186].

<u>Heat transfer measurements</u>. In geothermal areas, heat is transferred by various processes, such as fumaroles, steam wells, hot springs, steaming grounds, evaporation from hot pools and thermal conduction through the earth. In this paper, we will outline methods of heat transfer measurement which have been devised and improved to fit field work.

As a practical example, heat transfer measurements in the Owakudani and Sounzan geothermal areas of Hakone volcano are outlined. Total mass discharge from these areas amounts to 129 kg/sec and total heat transfer amounts to 10.24×10^6 cal/sec which is equivalent to 1×10^{22} erg/year, corresponding to a mesoscale volcanic eruption a year.

In Japan, as there are about twenty geothermal areas each having the same size as the Owakudani and Sounzan areas put together, the thermal discharge from all these areas may be estimated roughly to be 2×10^{23} erg/year. In addition to this, the energy released by volcanic activity, 7×10^{23} erg/year, by common hot springs, 1.1×10^{24} erg/year, and by the normal hot flow of nonvolcanic regions, 7.3×10^{24} erg/year, we can estimate the total energy released from the whole of Japan, escept that by earthquakes, to be about 9×10^{24} erg/year.

Heat discharged from a geothermal area can be defined as the heat flowing from deep ground to the surface in a unit time interval through a finite geothermal area. However, if horizontal heat transfer between adjoining areas is considered, this effect must also be taken into account. Heat transfer of geothermal areas may be classified into the following types:

- heat transferred by steam flow: Q_1;
- heat transferred by thermal water flow: Q_2;
- heat transferred by evaporation from hot pool: Q_3;
- heat transferred by thermal conduction through the earth: Q_4;
- heat transferred by gas flow: Q_5.

Thus, the total heat transfer Q can be written as:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$

There are many methods to measure the density of natural steam, regarded generally as the mixture of vapor and small water drops. But most methods which require complex equipments attached to the wellhead are not suitable for Japan's present purpose. A direct steam sampling method is a relatively suitable method for natural geothermal fields. This method consists of sampling a certain volume of the steam under the same condition at the wellhead and then weighing it. Fig. 32 is a rough sketch of the direct steam sampler. If the temperature of the sampling tube is lower than the wellhead temperature, then even if the pressure at the beginning is kept the same, steam condenses in the tube and the pressure falls causing further inflow of steam into the tube. If the temperature of the tube is higher than that of the wellhead, the effects may be different.

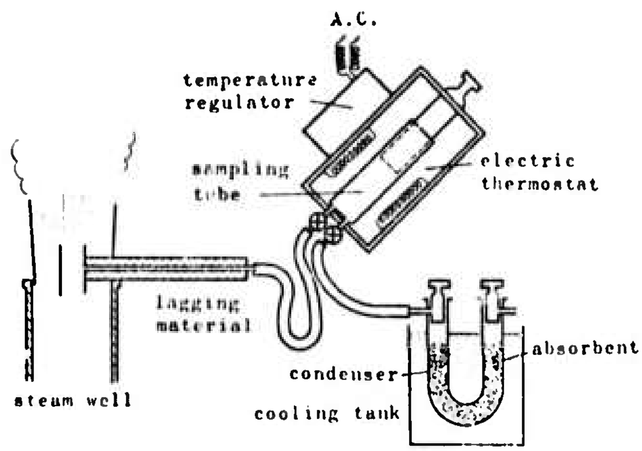


Fig.32. Direct steam sampler [187].

To measure the mass flow from natural fumaroles of irregular shape, we can use a bowl shaped collector over the fumarole. When the steam is ejected from an upper tube of the collector, we can perform the steam flow measurements using the above mentioned method.

For weak steam flow from so-called steaming grounds, R. F. Benseman in 1959 has devised a calorimeter suitable for geothermal field use. The Japanese also devised a calorimeter, similar to Benseman's apparatus, and is shown in Fig. 33.

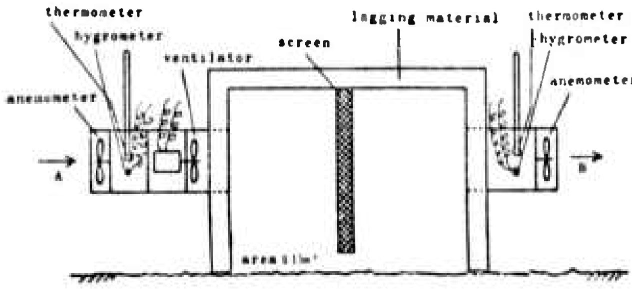


Fig. 33. Geothermal calorimeter [187] .

Air is made to enter through the inlet A and is blown off through the outlet B by a fan in the calorimeter. The mass of steam coming from the bottom of the calorimeter is given by

$$m = V(\sigma_{w2} - \sigma_{w1}) ,$$

where V is the volume of air passing through the calorimeter, and σ_{w1} and σ_{w2} are the absolute humidities of the air at the inlet and the outlet of the calorimeter.

Heat Q transferred by steam through the bottom of the calorimeter can be written as:

$$Q = V \sigma C_p(t_2 - t_1) + V(\sigma_{w2} i_2 - \sigma_{w1} i_1) ,$$

where σ is the density of the air, C_p the specific heat of the air, i_1 and i_2 the enthalpies of the steam at temperatures t_1 and t_2. Absolute humidities of the air σ_w can be written as :

$$\sigma_w = \frac{289.4 \, Ff_m}{t + 273} , \qquad g/cm^3 ,$$

where f_m is the saturated vapour pressure at temperature t ^{o}C, and F the relative humidity [187] .

Superheated steam in hydrothermal areas. Observations of natural steam have often shown temperatures higher than 100°C at the orifices of fumaroles or wellheads in various hydrothermal areas. This steam is called superheated steam. Thermodynamic condition of the natural steam has often been assumed as reversible adiabatic change in the course of the flow in a subsurface layer or wellheads. This shows the conservation of entropy and possibly leads to an incorrect conclusion that the superheated steam cannot originate from saturated steam whith liquid thermal water but from originally superheated steam.

It is, however, found that deep bored wells in such areas discharge the thermal water of sodium chloride type which is considered as the most possible origin of subsurface steam. Dynamic condition of the subsurface flow of steam is generally treated in a form similar to Darcy's equation, in which the velocity is proportional to the pressure gradient. This condition essentially founds on the equilibrium of the forces including the friction of flow and is contradictory to the conservation of entropy. Dacy's equation is then possible to be transformed to the thermodynamic condition of the conservation of enthalpy. The highest value of enthalpy of the steam in the state of equilibrium with deep thermal water is 669.7 cal/g at 240°C. It corresponds to that of the superheated steam of 163°C at the pressure of 1 atm. This temperature is expected to be the highest value of the natural steam which ascends from the region of thermal water to the ground surface. Such a high temperature has not been noted prior to this report [188].

Geochemical research. Extensive study on geochemical composits of geothermal waters over 30 large regions of Japan was conducted during the period of 1973 - 1975, yielding valuable data on various elements.

Japanese scientists are extremely interested in the study of rare earth elements of various geothermal hot springs. Applying

activation analysis, using Ge(Li) detector, studies of these elements provided comprehensive data. Lanthanum, samarium, europium, gadolinium, dysprosium, ytterbium and scandium content in Tatsumakijigoku and Umijigoku Hot Springs were determined by activation analysis, a lithium drifted germanium high resolution semiconductor detector being used. Samples of spring water, deposits from thermal water, core and pyroxene andesite were used for an analysis. The neutron irradiation was carried out by using a JRR-2 Reactor (thermal neutron flux 8×10^{13} n/cm^2 sec) for twenty minutes. The content of rare earth elements in acid hot spring waters were found to be higher than those in neutral or alkaline spring waters.

The relative abundance of the rare earth elements in the core sample almost coincides with the Clarke Numbers of the corresponding elements. On the other hand, the relative abundance of those elements in the hot spring waters and the deposits coincided with that in a fresh rock samples of pyroxene andesite [189].

An activation method in combination with an ion exchange method was studied for a determination of the rare earth elements in hot spring waters. The content of lanthanum, samarium, europium and scandium were determined in the water samples from Yunotsu Hot Springs and Ikeda Mineral Springs. The rare earth elements contained in 10 liters of water sample were coprecipitated with calcium oxalate. After ignited carefully, the recipitates were irradiated with neutrons by using the KUR (neutron flux 2×10^{13} n/cm^2 sec) for 5 hrs. Then the rare earth elements were separated radiochemically by ion exchange method, using 0.5 M ammonium citrate solution of 3.5 in pH-value as an eluant.

Radioactivity was measured by using the 512 ch PHA. The content of the rare earth elements in the water samples from Yunotsu and Ikeda were 0.08 - 0.13 μg/l La, 0.02 - 0.07 μg/l Sm, 0.005 - 0.008 μ/l Eu, and 0.4 - 0.8 μg/l Sc [190].

<u>Geothermal noise abatement</u>. The steam wells are extremely noisy when steam is ejected without mufflers. The frequencies of this noise range from a low to a very high frequency range. An ordinary expansion chamber-type muffler is not effective for noise of such high frequencies.

The noise contains high energy components in the high frequency range and the noise level increases with an increase in the flow rates of steam.

In the case of such high frequency noise, directional sound waves may exist in the chamber of the muffler so that the flat plane wave theory does not hold and the expansion chamber-type muffler is not applicable.

Fig. 34 shows measured characteristics of an ordinary expansion type muffler as shown in Fig. 35. The effectiveness

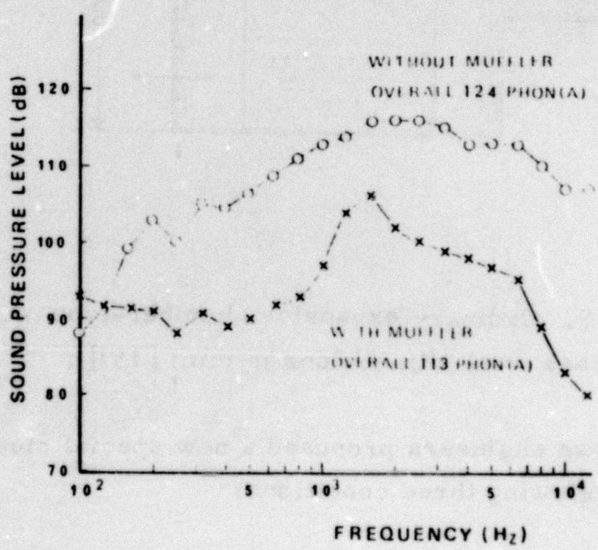


Fig. 34. Frequency spectra with and without ordinary expansion chamber-type muffler (dimensions in mm) [191].

of the ordinary muffler decreases considerably in high frequency ranges.

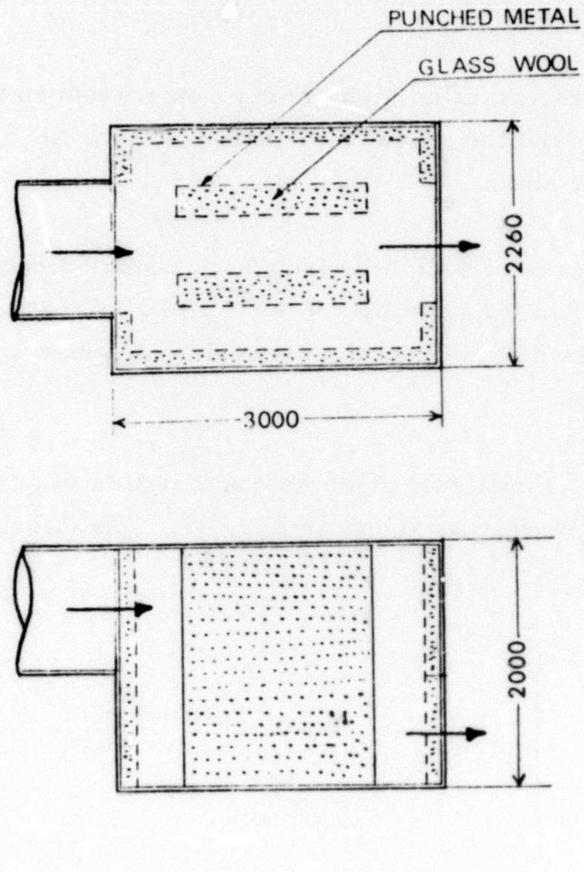


Fig. 35. Ordinary expansion chamber-type muffler with glass wool (dimensions in mm) [191].

Japanese engineers proposed a new special steam muffler to satisfy the following three conditions:

- good noise reduction, even in the high frequency range;

- very low resistance from steam flow, and

- easy to check deposit of scales and corrosion due to acid moisture.

The schematics of this muffler is shown in Feg. 36.

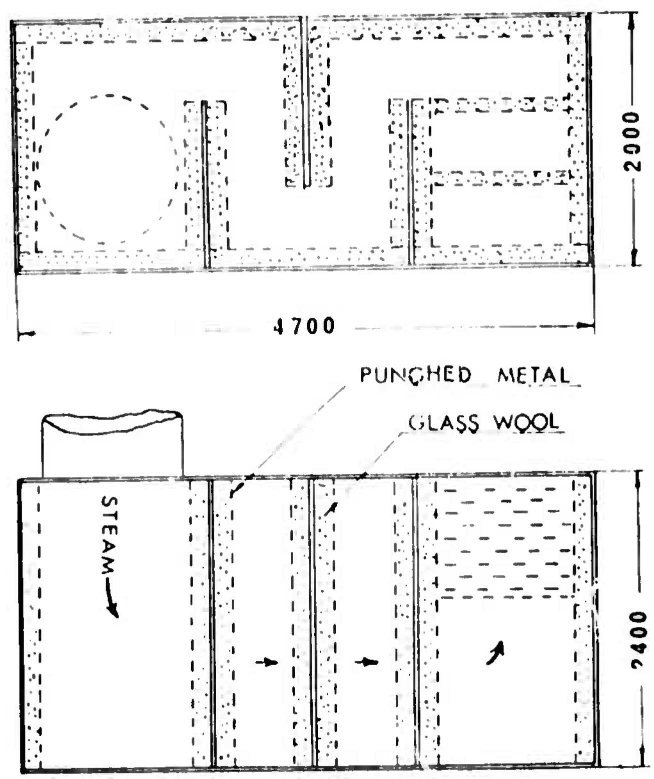


Fig. 36. Specially designed Japanese muffler (dimensions in mm)[191].

The muffler is applied to the power plant system as shown in Fig. 37. The mixture of steam and hot water from the well enters the separator first, in which steam and hot water are separated. The separated steam flows into the muffler through a six-inch diameter pipe. Sometimes it is ejected into the air through a bypass line.

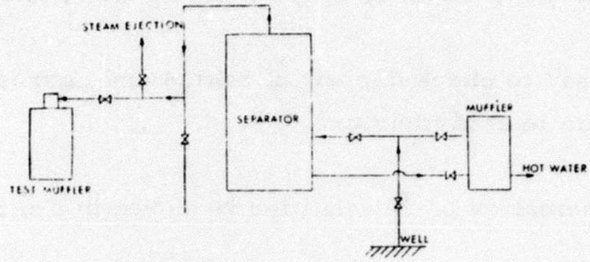


Fig. 37. Schematics of a steam ejection system with Japanese designed muffler [191] .

Fig. 38 shows observed values of sound pressure level, with and without the muffler. Considerable reduction of noise level, with high frequency components is obtained and the amount of noise reduction is about 40 phon by weighted scale A.

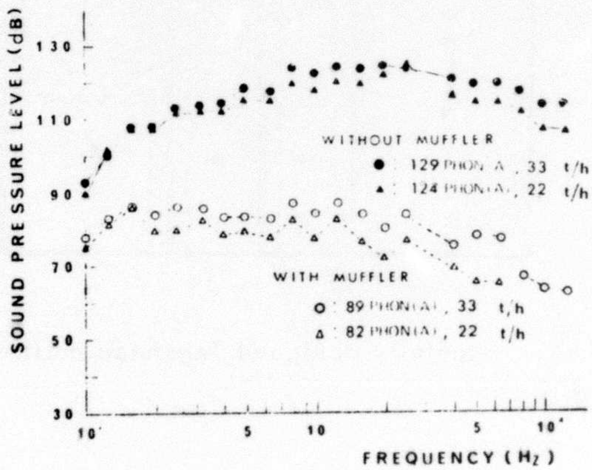


Fig. 38. Frequency spectra with and without Japanese designed muffler Fig. 36 [191] .

The attenuation of this muffler is shown in Fig. 39. However, the attenuation in the case of a small flow rate is larger than in the case

of a large flow rate. Evidently, the large steam flow rate generates secondary noise in the chamber of the muffler.

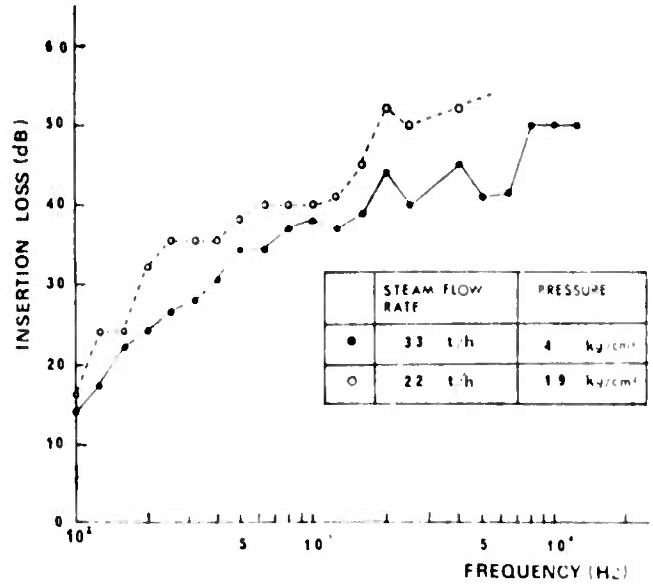


Fig. 39. Insertion loss for the muffler shown in Fig. 36[191].

This Japanese-designed muffler is successfully applied to the Otake geothermal power plant[191].

Generation of electric power. The utilization of geothermal energy for the production of electric power has been under consideration in Japan since 1920, and in this respect various investigations and exploratory drillings have been carried out in many geothermal fields.

The demand for electric power in Japan has been growing considerably in line with the development of various industries and improvements in the national living standards, and it is anticipated that such a trend will continue in the future.

Although geothermal power generating facilities are hardly expected to develop a large capacity in competition with conventional hydro or thermal power generating facilities, it has some significance as a new source of energy in Japan, in view of the following considerations:

- Volcanic geothermal fields are found in many places all over the country. It is not so difficult to find sites suitable for the high temperature water generating system in such geothermal fields. Therefore, it is feasible to construct a number of power plants with a small individual output but capable of a large total production;

- Since a wide transmission line network covering all the country already exists, these power plants can easily provide the power output of the network.

- Geothermal power generation will enable a saving, to some extent, in the amount of imported heavy oil which is expected to increase in the future; and

- It is estimated that the generating cost of geothermal power is low compared with conventional thermal power generation in Japan where the cost of fuel is high.

Reviewing the results of past research and exploration carried out in the geothermal field in Japan, the geothermal power generation by means of the high temperature water system is the most suitable means of development and that the further development of geothermal power generation by the said system will play an important role in the new phase of energy economy [193].

The utilization of geothermal energy for power generation has recently become the most important field of geothermal use.

Industries have been awaiting geothermal power because of the aboundant hot volcanic springs in Japan. The first attempt was made by H. Tachikawa, who carried out a trial power generation of 1 kW at Beppu in 1924. But the enthusiasm for and interest in power generation by geothermal sources have gradually faded away, mainly due to the rapid progress of hydraulic and thermal power plants. During the postwar years of electric power shortage, some trial geothermal power generations were attempted on a small scale at Atagawa (Shizuoka Prefecture), Narugo (Miyagi Prefecture), Beppu (Oita Prefecture) and Hakone (Kanagawa Prefecture). The Beppu plant was operating at an output of 30 kW in 1956.

Recently an upward trend of enthusiasm for geothermal power reappeared. As a result, in 1966, a 20 MW plant and in 1967 a 13 MW plant were constructed at Matsukawa and at Otake respectively. Further, exploitation is being actively carried out at present at Hachimantai (Akita Prefecture), Onikobe (Miyagi Prefecture), and Hatchobaru (Oita Prefecture), from all of which we can expect good results, as promising production wells have already been exploited [103].

The geothermal potentialities of Japan are evaluated at several to ten million KW. This estimate may become conservative in the near future [127].

Based on a geothermal resources survey, it has been estumated that Japan can produce about 10,000 to 20,000 MW of electricity [200]. According to long-range forecasting, the total production of geothermal electricity by the year 2000, could be 8,800 MW (about 1.6% of all electric production capacity) [202]. There are over 10,000 geothermal energy sources with a heat volume equivalent to seven million tons of coal annually [201].

Noticable progress has been made by the Japan electrical industry in manufacturing geothermal power plants for domestic and foreign use [127].

The following are some highlights of Japanese geothermal power stations and pertinent components:

Beppu geothermal power plant is situated in northeastern part of Kyushu Island in a highly volcanic zone characterized by strong surface manifestations comparable to some in New Zealand.

Three test wells have been drilled to a depth of 100 m with a temperature of 145°C. A 75-mm orifice produces 3.4 metric tons/h of steam and water, one-third being steam.

Thirty kw of geothermal energy are geing generated [14].

Hachimantai geothermal power plant is situated in Akita Prefecture on Honshu Island where construction on 10 MW capacity started in 1971, from production wells of 850 and 1042 m depth [127].

Additional data on this plant is lacking.

Hatchobaru geothermal power plant, situated on Kyushu Island near the Otake geothermal power station, is under construction and will have a capacity of 50 MW (by other source 55 MW) [195].

This station, under authority of the Kyushu Electric Power Company, will be equipped with one steam-condensing turbine of 55 MW capacity, manufactured by the Mitsubishi of Japan. It is a double pressure turbine utilizing steam flashed from hot water. This is the advanced cycle for full conversion of geothermal energy into electricity (Fig. 40).

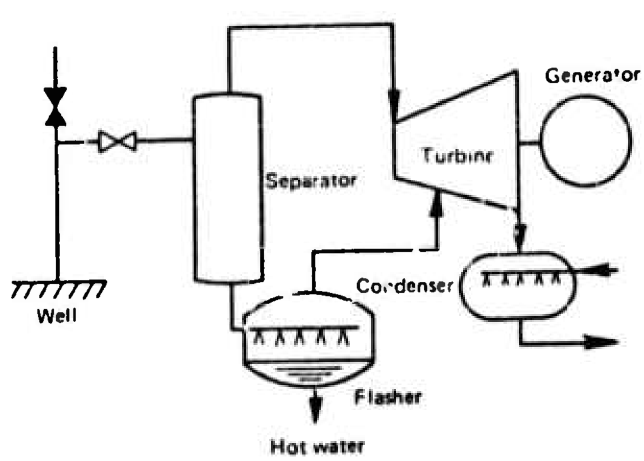


Fig. 40. Schematic of the energy cycle for Hatchobarn geothermal power station [172].

The hot water coming from the steam separator is flashed to generate steam, which is fed into the turbine at a suitable stage of the bladings, and which results in the lower capital and operating costs per kw generating capacity. To enhance efficiency and economy of the initial and operating costs, Mitsubishi has developed method of transporting the mixture of steam and hot water for separation and flashing right at the turbine side. Naturally, separation and flashing may be done at the wellhead for transportation to the turbine. The merits of this cycle are: increased power generation, lower generating cost per kw/h, decreased hot water discharge, and lower wetness of turbine exhaust steam [172].

Steam force parameter is calculated at 7 to 2 kg/cm^2, with temperature 169 to 102°C respectively, and pressure of 0.1 kg/cm^2 [196].

Matsukawa geothermal power plant, situated in the northern part of Honshu Island, began its operation in October 1966 with a 20 MW condensing turbine generator, and an annual output of about 173 million kw/h (Fig. 41) and is the first power plant of this kind in Japan.

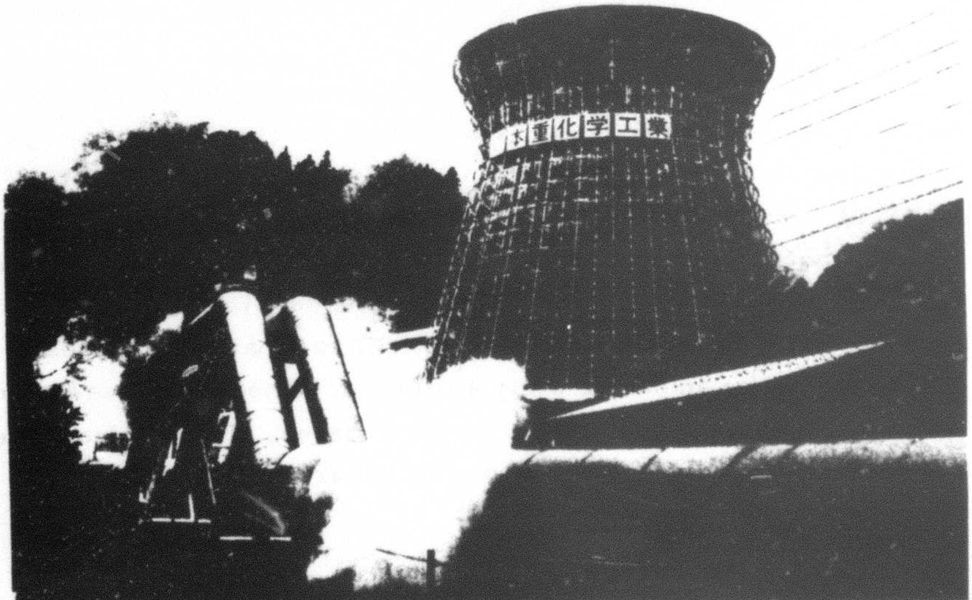


Fig. 41. Matsukawa geothermal power station [199].

Major characteristics of the Matsukawa geothermal field are: reservoir temperature - 230°C; reservoir fluid - mostly steam; enthalpy - 550 cal/g; average well depth - 1,100 m; fluid salinity - <1,000 ppm; mass flow per well - 50,000 kg/hr, and amount of noncondensable gases - <1 percent [10].

Compared with other plants, there are no characteristic differences in the installations or the equipment such as the geothermal wells, steam line pipes, turbine, condenser, cooling tower, ejectors, or other electrical equipment, but special caution was paid in choosing them as they were to be set in the narrow mountainous area and to be used for geothermal steam (Fig. 42).

However, some faults which developed during the three years of operating are: the breakage of the turbine blades, the abnormal vibration of the rotor caused by an iron piece attached to the shroud ring of the first stage, the decrease of vacuum caused by the corrosion of the tail pipe on the first stage of the ejecting cooler, the instability caused by the puncture of the selenium arrestor attached to the static exciter.

The following is a general outline of the main equipment of the plant:

The turbine generator has a turbine rating of 20,000 kW with 3.5 kg/cm^{2}G, 147°C, 208 t/h inlet steam condition and exhausting at 95 mm Hg absolute pressure. The generator rating is 23,500 kVA, 0.85 power factor, 11 kV, air cooled, 3000 rpm, and the generator is furnished with a static excitation system. The unit is operated at 20,000 kW. Because the dust in the steam may cause the throttle type valve to stick, two main stop valves of swing check type and three control valves of butterfly type are used. The turbine has four single-row impulse stages. The turbine blades are 12 percent chrome, and the casing is carbon steel.

The barometric condenser is designed to condense the exhaust steam of 194 t/h and to produce a vacuum of 95 mm Hg absolute pressure. The noncondensable gases of 2234 kg/h from the condenser are ejected to the atmosphere by the steam jet gas ejectors of two stages. The condenser shell, 4.7 m diameter and 10.3 m high, is carbon steel plate coated with stainless steel and epoxy paint on the inside.

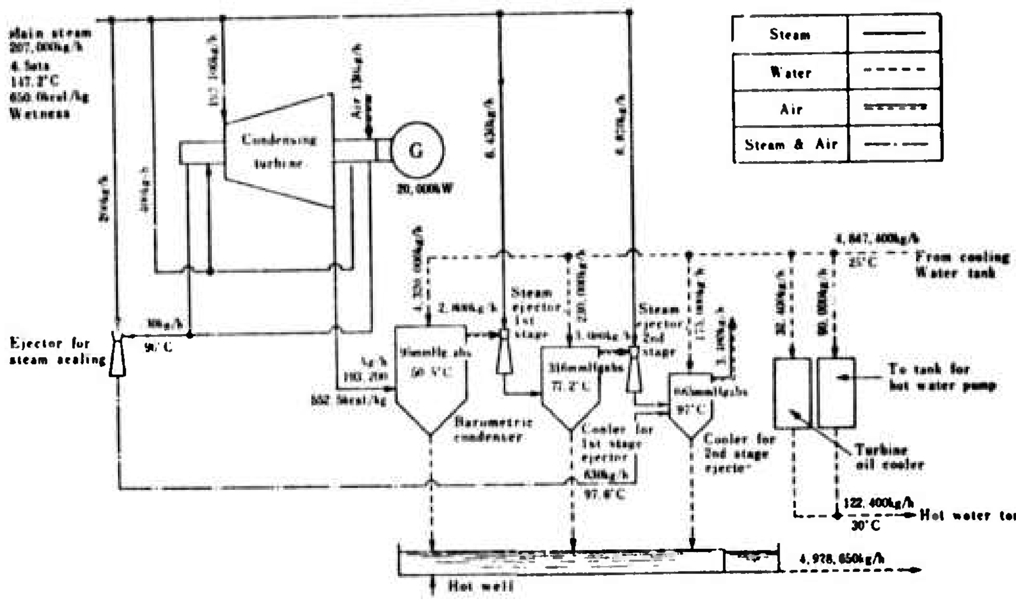


Fig. 42. Heat flow diagram of Matsukawa geothermal power plant [122].

The cooling tower is designed to cool 5000 m^3/h of water from 47°C to 25°C and is a natural draft type. The tower, 45 meters in diameter at ground level and 44.6 meters high is sheathed with 10 cm thick vacuum concrete panels set to the steel pipe shells, and it has 1.6 m of plastic packing. The water distribution system consists of steel pipes with plastic spray nozzles.

Except for the use of the static excitation system and other changes required by the corrosive atmosphere, standard electrical equipment is used. The main step-up transformer is rated 23,500 kVA, 11 kV/155 kV, 3-phase, 50 Hz, and the plant auxiliaries are fed from 2500 kVA transformer, 11 kV/3.5 kV, 3-phase.

The electrical power produced at Matsukawa is supplied to the Tohoku Electric Power Company, Ltd. network by means of a 20 km, 155 kV transmission line[198] .

After much difficulty in the first three years of operation, the Matsukawa is presently under smooth operation. However, two 20 MW additional units are programed for 1980, as well as a recreation center, greenhouse and fish raising projects [127] .

Onikobe geothermal power plant, is situated in the Onikobe geothermal area, northwestern part of Miyagi Prefecture, northeast Japan. This area is a wide basin extending roughly 9 km from north to south and 7 km from west to east. Near the center of this area is the Katayama geothermal field in which many hot springs and fumaroles are distributed. For developing geothermal power this area has been suveyed since 1962. To study the geological structure and the steam characteristics, various types of prospecting were carried out during the 1962 - 1968 period. The first production well was drilled from December 1968 to April 1969 [194] , to a depth of 980 m and to a bottom temperature of 288°C [127].

Construction of the Onikobe geothermal power plant started in April 1973, with completion planned by the end of 1975. The station will be equipped with one steam-condensing turbine of 25 MW capacity. Steam pressure at the wellhead is measured at 4.5 kg/cm^2, 147°C temperature, and a discharge of 220 tons/hour. This plant will utilize 12 wells, with undisclosed total discharge capacity [195] .

Onuma geothermal power plant is situated in the Toroko-Onuma geothermal area, part of the Northern Hachimantai geothermal region, of the Akita Prefecture. The area is known as one of the volcanic regions of Japan, but at present, Yakeyama is the only volcano which shows some activity. The area is abundant with thermal springs, fumaroles and solfataras. In 1965 an extensive geological, geochemical, photographic, mineralogical, and detailed electrical survey and test drilling was started to a depth ranging from 446 to 1,500 m. Provisional isotherms were drawn from the seven holes drilled during 1967-1968, showing close relationship with the volcanic center, surface manifestations, altered areas and electrical anomalies.

In November 1968 a well produced about 25 tons of steam and 65 tons of hot water per hour with two additional wells by 1970 to warrant geothermal steam production and the construction of a 10 KW power station [194].

The Onuma geothermal power plant is equipped with a one cylinder, four-stage, steam-condensing turbine with a capacity of 10 MW. Steam pressure at the stop valve will be 2.5 kg/cm^2, with a temperature of 127^{o}C, and steam discharge of 107 tons/h. From November 1973 to September 1974, station produced 37,000 MW/h of energy (average capacity 4.8 MW with 9.9% loose on station operation). During this period several breakdowns resulted in 810 hours of shutdown [203]. Operation of this plant started in 1973.

Otake geothermal power plant is situated in a highly volcanic zone of the central-eastern part of Kyushu Island.

In 1949, the Kyushu Electric Company started a preliminary survey at several areas in Kyushu, for the purpose of generating electricity by geothermal energy. From 1953 - 1956 they began investigation at Otake geothermal field, and drilled four test wells, but could not develop superheated steam and the project was discontinued.

In 1961, they began the study of the use of geothermal energy by the flashed steam from a steam-water mixture, and exploration of the Otake geothermal field was put into operation. Also between 1963 - 1966 five productive wells were drilled with very powerful discharge.

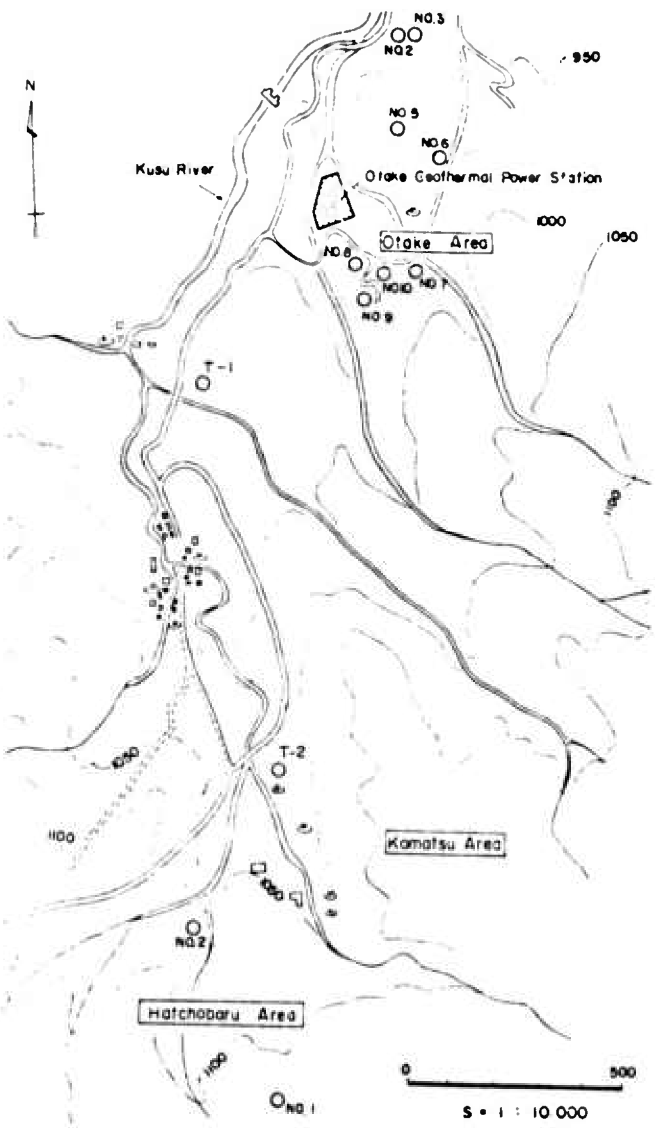


Fig. 43. Map of Otake geothermal power plant and production wells [194].

Construction of the power plant started in January 1966 and was completed in about 19 months. The plant went into commercial operation in August 1967 [194].

Otake geothermal power plant, the first steam-water mixture type power plant in Japan has been operating successfully since 1967 with a 12 MW output. In comparison with the other geothermal power plants in the world, most of which use superheated steam at about 3 - 13 kg/cm^2, the Otake geothermal power plant utilizes low-pressure saturated steam of 1.5 kg/cm^2 separated from a mixture of hot water and steam.

The design of this plant is based on the study and development of the following elements: characteristics of geothermal wells, chemical properties of steam and hot water, selection of best material, development of efficient water separators and orifice water-level control method, transmission of geothermal fluids (steam and water), and development of jet condensers.

The features of Otake plant are as follows:

Rated output	10 MW
Operation output	12 MW
Maximum output	13 MW
Steam condition	1.5 kg/cm^2 saturated
Condenser vacuum	687 mmHg
Geothermal well	5 X 8 inches in diameter
Steam turbine	single cylinder impuls condensing
Condenser	barometric spray type
Cooling method	forced draft cooling tower
Gas extractor	reciprocating vacuum pump

The steam condition was selected to get the maximum available energy from the geothermal well, and also to avoid power

down in case of scale deposit. The condenser vacuum was selected considering all the factors, such as turbine output, turbine last blade length, size of the condenser and cooling tower, and required number and power for the cooling water pump, hot water pump, cooling tower fan and vacuum pump. In the case of geothermal power plants steam quantity is apt to increase in the future. Therefore, in order to be sure of stretched power operation in the future, turbines are designed to have a maximum output of 13 MW. Overall inspection after 8670 hours of continuous operation showed no damage by scaling and corrosion to all equipment.

In general, commercial success of the Otake power plant, which uses low-grade geothermal energy, has thrown a bright light on the future of geothermal power generation in Japan, because it is expected that there are many other geothermal areas which yield only a mixture of steam and hot water.

The plant is composed of the equipment shown in Fig. 44 and 45 and its main characteristics are shown in the following table.

Steam Turbine	Type			Single Flow Impulse Condensing Unit
	Rating Output		kW	10,000
	Max. Capability		kW	13,000
	Speed		rpm	3,600
	Steam Condition (at MSV Inlet)	Pressure	ata	2.5
		Temperature	°C	(Saturated) 127
	Exhaust Pressure	Exh. Chamber	ata	0.11
		Condenser	ata	0.10
	Steam Consumption (at Rating)		t/h	113
	No. of Stages (Rateau)			4
	Length of Last Blade		mm	420
	Allowable Inlet Steam Pressure		ata	5.8
Condenser	Type			Barometric Jet Condenser
	Shell Pressure		ata	0.10
	Cooling Water Temperature		°C	26
	Warm Water Temperature		°C	41.4
	Cooling Water Quantity		m^3/h	3,900
Vacuum Pump	Type			Motor-driven Reciprocating
	No. of Units			3
	Suction Pressure		ata	0.092
	Delivery Pressure			Atmospheric Pressure
	Extraction Capacity		m^3/h	(per Unit) 4,620
	Net Power (Starting Rating)		kW	(per Unit) 105 55
Cooling Tower	Type			Cross Flow Forced Drafting
	No. of Shell			3
	Capacity		m^3/h	4,200
	Warm Water Temperature		°C	41.4
	Cold Water Temperature		°C	26
	Design Wet-bulb Temperature		°C	17
	Type of Blower			Vertical Axial Fan
	Cooling Air Quantity		m^3/min	(per Shell) 16,500
	Net Power		kW	(per Shell) 66

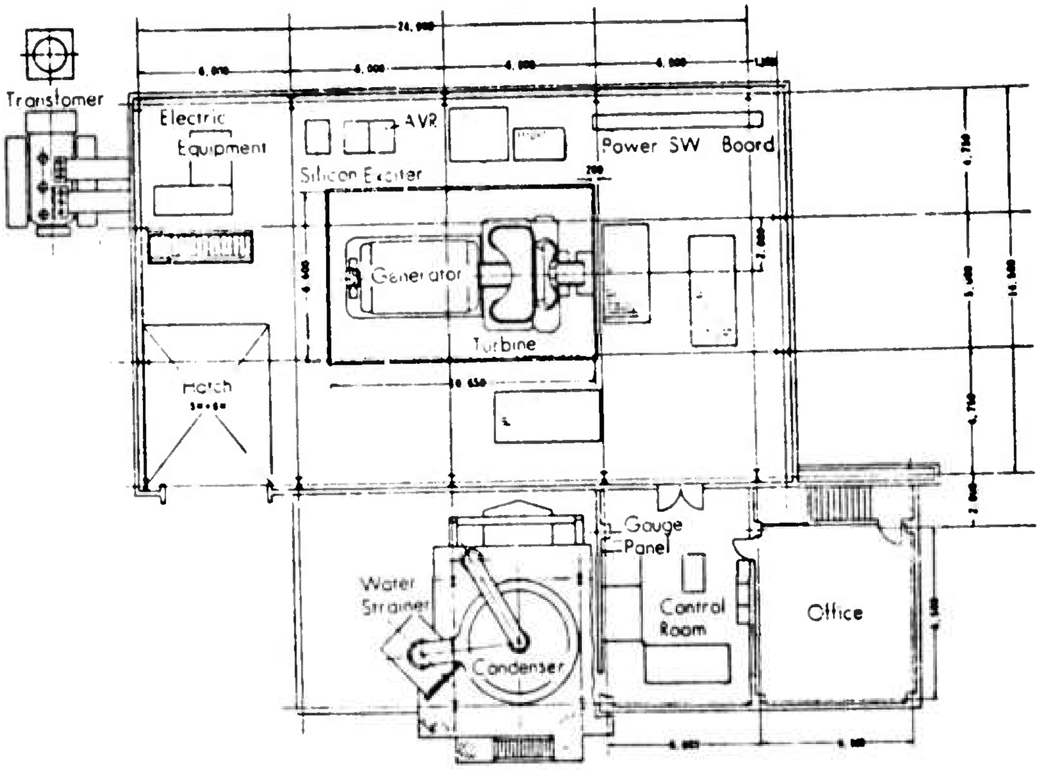


Fig. 44. Plan of Otake power plant (dimensions in m)[205] .

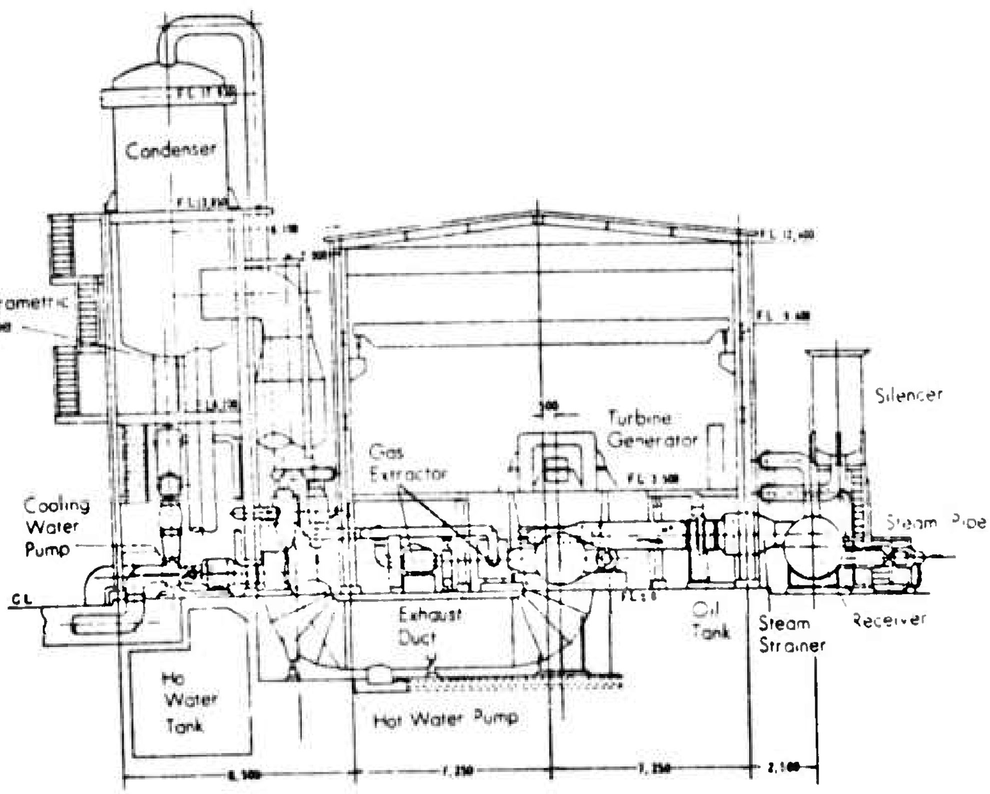


Fig. 45. Cross section of Otake power plant (dimensions in m)[205] .

During the 1967 - 1973 period, Otake geothermal power plant operated for 55,608 hours and produced 500,000 MW/h of electric energy. By 1980, projected capacity of this plant is set at 60 MW [205].

A few hotels were using some of the natural hot springs, before the Otake geothermal field was exploited. According to the progress of exploitation, the hot water is being piped to the Jizobaru reservoir, which is about 4.5 km from the Otake power plant by aqueduct, for water pollution prevention purposes. The aqueduct is made of reinforced concrete (1.0 m wide, 1.1 m deep) and water flows by gravity.

About 170 t/h of hot water is being led off from the aqueduct to private houses, sanatariums, hotels and botanical gardens. The hot water is mostly used for heating, bathing and cooking. The rest of the hot water is fed into the Jizobaru reservoir [194].

Future developments. - The following are some geothermal areas and fields for future development of geothermal energy:

Narugo is situated in the northern part of Honshu Island characterized as a volcanic zone. About 22 wells have been drilled to a depth of 213 m, reaching a temperature of 175°C. Tests indicate that from two to seven metric tons/h of a mixture of steam and hot water can be obtained through a 45-mm orifice. The amount of water in this mixture varies from one to six metric tons/h [14]. By its potential, this area is considered for production of geothermal energy.

Obama area situated in the western part of the Kyushu Island, is characterized as a highly volcanic zone.

About 80 wells have been drilled, producing steam and water at 130°C. The total production is estimated at 4,200 metric tons/h, which would correspond to 70MW if used to generate electric energy [14].

Otake and Hatchobarn geothermal areas, besides the described geothermal plants in operation, is planned for production of 180 MW based on reservoir capacity[127].

Sendai geothermal power plant will be erected in the near future with a capacity of between 20 and 25 MW. Four production wells are in completion stage [200].

The Takinokami geothermal area, 8 km southeast of the Matsukawa area, is situated along the upper reach of the Kakkonda river flowing around the western side of the Iwate volcano and discharging into the Shizukuishi basin. Takinokami is synonymous with Takinoue.

Parellel to the goethermal investigation in the Matsukawa area, the Geological Survey collected data on geological sequences and the structure of Tamagawa welded tuff and Yamatsuda formation in this area, because they are expected to be situated under the Matsukawa area. After that, the Geological Survey carried out geothermal investigation including detailed geological survey, electric survey, temperature survey at a depth of 30 m and drilling of a research well 400 m deep, for the purpose of clarifying geothermal conditions in the Yamatsuda formation, and other older formations (Fig. 46).

According to the result of the electric survey made along the line cutting through the anticlinal axis on the north side of the river, a vertical distribution of resistivity curves, representing high values in dacite of the upper part of the Yamatsuda formation, low values in marine sediments and again high values in green tuff, was obtained for understanding the subsurface structure in this area.

A temperature survey measured at a depth of 30 m and made at about fifty points was carried out to find out the relation of thermal manifestations and geological structure. Judging from the distribution of isothermal lines, there are two high temperature zones. One is

that along the folding axis, the other is that along the fracture zone through the fumarolic area in the southern part of this area. However, there remains the question of why low temperature exists between these two high temperature zones.

To clarify the above mentioned problem and occurrences of geothermal fluids in the Yamatsuda formation and other older formations, a research well 400 m deep was drilled in 1967 outside the high temperature zone occupying the southern part of this area.

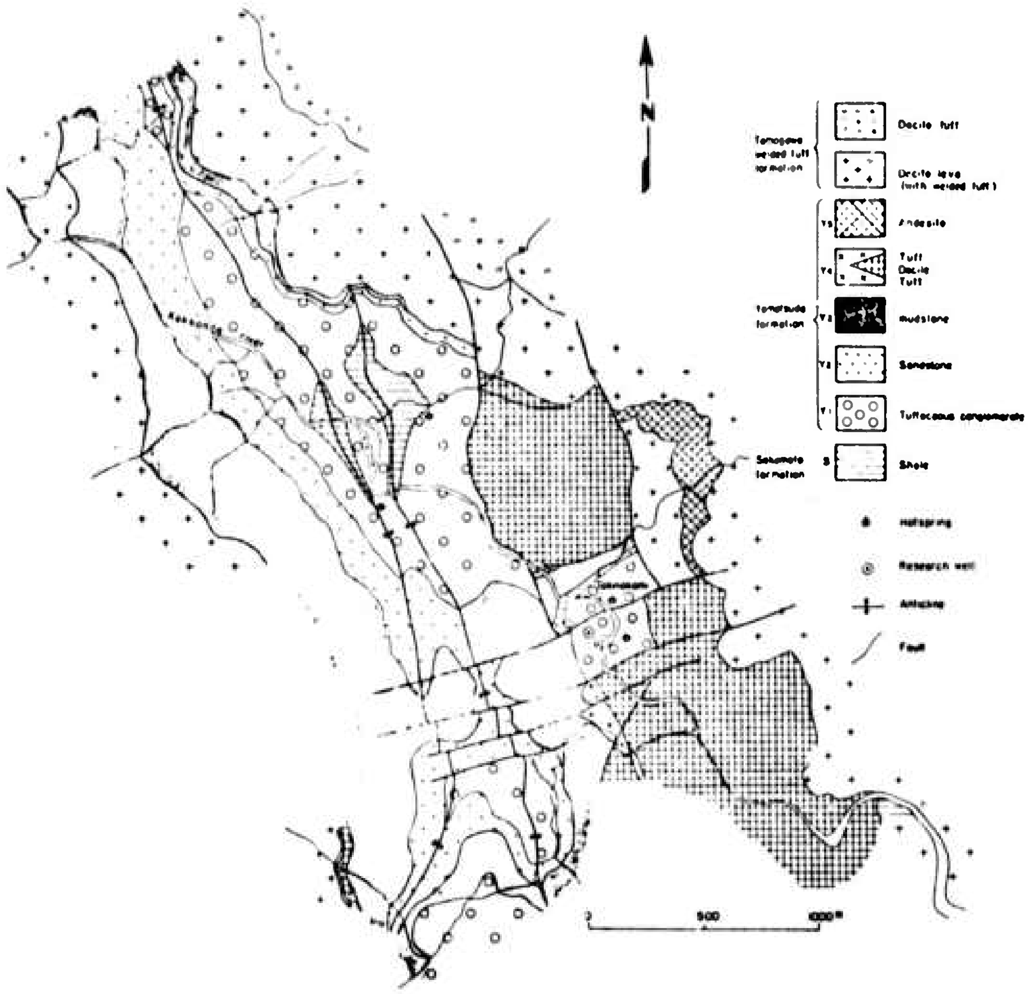


Fig. 46. Geological map of the Takinokami geothermal area[194].

In conclusion, it is summarized that the Yamatsuda formation has comparatively many cracks in the part of sediments consisting of sandstone and tuff, but few in dacite; therefore, the low temperature zone has been formed by the effect of an intrusive body of dacite with poor cracks.

On the basis of data obtained from the investigation by the Geological Survey, the Japan Metals and Chemicals Co. Ltd, is making a plan of geothermal exploration including seismic survey and test drilling in this area [194]. In contrast to Matsukawa, Takinokami offers many fumaroles and hot springs and a large area of hydrothermal rock alteration. Exploratory drilling is programmed for the year of 1971 and a power plant of 35 - 50 MW is anticipated in 1973 - 1975 [127]. However, data on this activity is lacking.

A 1970 report indicated that in the Takinokami area the exploitation will proceed prior to that of Matsukawa, as the cost of the construction of the Takinokami plant will be cheaper, and the whole output in this area will reach an estimated capacity of 200 MW [197].

Takenoyu geothermal area is situated in the northern part of Kumamoto Prefecture in Kyushu, 7 km from the Otake geothermal area beyond Mt. Waita, one of the Quaternary volcanoes included in the Kuju volcanic group.

This area consists of Hohi volcanic complex which is known as a reservoir of geothermal fluids in the Otake area, and Yamakawa tuff breccia, both of which are covered by younger Misokobushi lava and lava dome of Waita volcano. The Hohi volcanic complex is found on the north side of the Takenoyu fault running through Takenoyu and Haganoyu hot springs in a east-west direction, while the Yamakawa tuff breccia is mainly distributed on the south side of the fault. Besides the Takenoyu fault which is considered to extend in a southeast direction through the center of Waita volcano and the Otake geothermal area, there may be several faults in this area. The geographic distribution of volcanic bodies in the Kuju volcanic region

suggests that their arrangements have been controlled by subsurface structure formed in the basement rocks.

Along the Takenoyu fault, there are many fumaroles in the Takenoyu and Haganoyu areas and thermal water named Shinyu issues from Yamakawa tuff breccia, located on the south side of and 400 m from the fault.

In 1961 and 1962, the Yahata Iron Company Ltd. drilled two test bore holes for the purpose of geothermal exploration. The bore holes were drilled in the Takenoyu area; on the north side of the fault and in the area where the Hohi volcanic omplex is distributed. Soon after blow out began, well A-1 stopped emission of steam and hot water because of the precipitation of calcium carbonate deposited in the bore hole, while well B-1 discharging 0.92 t/h of steam and 1.72 t/h of hot water at the beginning is still emitting, though chemical and physical properties have changed.

However, the company gave up the exploration in 1963 for financial resons and after that, the Kumamoto prefectural government did measurements of flow discharge of steam and hot water emitted from well B-1.

In order to obtain data on the occurrence of geothermal fluid in this area, the Geological Survey carried out geothermal investigation including geological mapping, electric and gravity surveys and test drilling from 1965 to 1968. In addition to the investigation by the Geological Survey, the prefectural government also made a temperature survey by drilling five shallow holes 100 m deep in 1968.

According to the result of the gravity surveys made in 1964 and 1965, it is reported that fumarolic and hot spring areas distributed on

the westside of Waita volcano are included in anomalous areas of low gravity. Then, from the result of the electric surveys, it has become clear that a low resistivity layer is distributed all over this area with a thickness of 100 - 150 m. Five shallow wells made by the prefectural government were drilled for the study of not only the underground temperature of this area, but also the geological properties of the low resistivity layer. The result of drilling showed that Yamakawa tuff breccia and Hohi volcanic complex have suffered alteration, as far as to the depth of 100 m from the surface, though the temperature becomes lower in the outside area going away from Takenoyu ard Haganoyu. Thus, whether such rock alteration is related to the present geothermal activity or not remains a problem.

In the autumn of 1968, a research well 310 m deep was drilled by the Geological Survey at a point between Takenoyu and Haganoyu and on the south side of the fault. According to the observation of core samples, the boundary of Yamanoyu tuff breccia and Hohi volcanic complex is found at the depth of 200 m. The former is altered remarkably and the latter also contains zeolite and calcite veins. The underground temperature is relatively low in the former, but as soon as the borehole reached the latter, the temperature increased rapidly and mud water for drilling was soon lost. The maximum temperature was 200°C at the bottom of the hole. As it become difficult to continue drilling on account of the escape of mud water and the rapid increase of temperature in the borehole, drilling work was abandoned at a depth of 310 m, changing the scheduled depth from 400 m. After a 2 inch throttled pipe was put in the hole, the emission of steam and hot water bagan without artificial lifting of the water column. Shut-in pressure at the orifice is 10.5 kg/cm^2 and the amount of discharge of hot water is 26 t/h at 2.0 kg/cm^2, though the amount of steam has not yet been measured.

Based on the idea that the geothermal conditions concerning the reservoir are better on the south side of the fault than on the north side, two productive wells 500 m deep were drilled by the prefectural government in 1969 [194].

Very promising results have been obtained by preliminary exploratory drilling in Takenoyu geothermal area. A temperature of 200°C has been measured in a 2" diameter well at 311 m. Production of water and steam was obtained and development drilling is under way [127] .

In September 1972 drilling was started on test wells to obtain geologic data and chemical characteristics of hot water and steam in the Takenoyu area where a geothermal power plant of 50 MW capacity is in the final planning stage [206] .

Since a large portion of the energy resources of Japan is dependent on imports, the development of geothermal energy is being attempted in order to secure domestic sources of energy and also to obtain an inexpensive and stable source of electricity. Some of these projects have specific purposes such as supplying power for metal refining.

Under these circumstances, the success in power generation at Matsukawa and Otake together with favorable results elsewhere indicate the possibility of the future development of geothermal power generation in Japan [194] .

It has been estimated, that by 1985 the overall geothermal electric energy of Japan will reach about 11,420 MW capacity.

Other applications of geothermal resources. Geothermal resources are also being considered for diverse exploitation and most possible uses, whether of low - or high-temperature sources, appear to be economically viable with great advantages to domestic and industrial developments.

Besides generating electric power, geothermal energy has broad application in several fields. Only the major projects of basic interest to respective fields will be briefly outlined to illustrate the degree of multipurpose exploitation of geothermal resources in Japan.

Agricultural utilization of geothermal resources is on a small scale of about 8,000 m^2 of greenhouses, some eel fisheries and an alligator farm[127] .

Attempts have been made to utilize hot springs practically for industrial purposes other than that of taking baths. Such facilities, on a fairly large scale, are, for example, those in Shimokamo (Shizuoka Prefecture), Beppu City (Oita Prefecture), Ibusuki City and Kagoshima City (Kagoshima Prefecture), etc. In Shimokamo hot water of about 90°C was drawn into the glasshouse through a steel pipe, dating from 1916. This was for cultivating melons, flowers, etc., and in 1919 the glasshouse was extended up to 825 m^2. Today the facilities not only cultivate garden plants but also hatch eggs, raise poultry, as well as being used in brewing, distillation, or other processing. As of the end of 1968, in the case of Beppu City which is famous for its hot springs, 54 of the 2132 spring sources were utilized for horticulture, and 254 for tourism and other purposes. In Ibusuki City, as of the end of 1967, 106 of the 571 spring sources were utilized for horticulture, six for fish breeding and one for brewing and distillation.

In Beppu City, Abe Garden exclusively cultivates symbidium in one 100 m^2, four 50 m^2 glasshouses totaling less than 300 m^2 in area, employing only two workers and pumping hot water at 25 - 30 l/min at a temperature of 70°C. The operator of this garden sends the products as cut flowers by air to Tokyo, Osaka, and Kobe. He accurately meets the demands of these markets, and this is a particular case of a skilful specialized horticulture operation, which is able to influence market prices in the large cities while operating from a local district. Further, Yamada Garden, Minami-Izu-machi (Shizuoka Prefecture), purchases large quantities of various cacti and fresh plants from specialized plantations in the Kansai area (western Japan), cultivates them in a 590 m^2 plastic greenhouse heated with hot water, and sells them as small potted plants at stores in several towns and cities including Shimoda.

At Eishoen, Minami-Izu-machi, where salty hot spring water of 100 l/min at a temperature of 93°C is pumped up from 49 m in depth through pipes of 63 mm in diameter, is distributed to hothouses and the like through 50 mm or 60 mm pipes. This hot water is used for four months from December to March or April, according to season, for heating hothouses. The cultivating facilities consists of a completely roofed steel-framed glasshouse and a 100 m^2 vinyl house, where melons, tomatoes, cucumbers and other fruits and vegetables, flowers such as lilies, chrysanthemums, etc., papayas and leaf ornamental plants are mainly cultivated. Papayas seems to be gathered at any time throughout the year. The cultivating areas are 1000 m^2 for fruits and vegetables, 1000 m^2 for flowers and about 100 m^2 for ornamental leaf plants.

Oita Prefecture Hot Spring Heat Utilizing Agricultural Research Institute, was established in 1956 for the purpose of studying the cultivation of plants for tourist purposes. These include highly ornamentla tropical plants and other ornamental plants. The Institute also studies the cultivation of vegetables and flowers by utilizing hot spring heat and the cultivation and selection of seeds of plants unable to be grown on dewy land due to temperature conditions, etc. It is also engaged on physiological studies, on studies of nutrition for increasing plants and studies on the agricultural processing of plants. The total site area is 33,520 m^2, where there is a 1082 m^2 research hothouse and a 355 m^2 ornamental plant hothouse. The spring source is steam issuing well with a Pitot-tube, pressure of 8 kg/cm^2 and a temperature of 120°C.

<u>Chemical by-products</u> such as sulfur extracting operations are conducted by the Kokonoeyama Sulfur Mining Plant. The plant started operations in 1896, but reference literatures indicate that the naturally accumulated sulfur had been extracted for a long time before. It is supposed that naturally accumulated sulfur contained in erupting gases from the volcano had been extracted by local people.

The present method used for extracting is still very primitive; erupting gases from the volcano are introduced into a long flume, in which the temperature of the erupted gases gradually falls. The flume is designed to have a length so that the temperature of the gases at the outlet of the flume is maintained at 110°C - 120°C.

Heating and hot water supply with thermal waters have been used since 1916. The construction of geothermal district heating systems involving comparatively long distance transmission of thermal waters has been reported in the following localities:

An 11.5 km long transmission line carrying 14 l/sec of 70°C water from the Sarukura springs to the town of Towata, was constructed in 1963.

A 12 km long transmission line in Okawa area was built in 1963. It carries about 22 l/sec of 70°C water and supplies 3,000 houses with heat on an area of 260 hectares.

A district heating system was built for the Ukiyama area in 1965, comprising 900 houses on 100 ha. The system is equipped with a boiler plant that can heat the water to 55°C. The total length of pipe is 12 km.

A district heating system for the city of Aomoir was constructed in 1966 - 67. It supplies 140 houses, including 34 hotels, and the population is 3,600. The water is supplied from the Asamushi hot spring area at a flow rate of 22 l/sec and 60°C. The natural springs have temperatures in the range of 40 - 70°C.

Attention has been given to the possibility of using waste heat from geothermal power stations for domestic heating.

In Japan various types of pipes laminated with synthetic materials are used instead of steel pipes in order to avoid corrosion problems associated with mineralized geothermal water [141].

The transportation and supplying system of such hot water is applied not only to hot spring water, but also to hot water exhausted from geothermal power stations after electrification, and two or three plans are now in preparation.

The hot water used in the cooling process of a chemical factory was applied by the same system, and has also supplied 4000 houses. The supplying plan was completed at Onahama city in 1969 [207].

Japanese engineers have conducted unique tests utilizing geothermal water for heating the roads in winter on the Hokkaido Island by coil steel galvanized pipes (50 mm in diameter) laid 300 mm under the road pavement. With outside air temperature of minus 8°C, the pavement temperature is 2°C. Water temperature of 83°C at the intake and outside air temperature of minus 6°C, changes to 43°C at the outlet [208].

<u>Salt extraction</u> in Japan is on very limited scale. A few salt extraction plants use triple-effect vacuum evaporators, and the present equipment is too small for economical operation.

The Ikeda Geothermal Saltmaking Plant situated near Shikabe village, Oshima Administration Area, Hokkaido, is provided with an open-air heating tank, roofed concentration tank and a refining building in a site area of about 20 ares (2000 m^2), into which hot water and steam are introduced from the gushing well of 203 mm in bore diameter and of about 71 m in depth to be used for heating sea water.

The method of saltmaking is characterized by floating 200 shallow tanks of 91 cm X 182 cm made of zinc-steel plates in the open-air

heating tank, and sea water is heated with hot water from the bottom of the tank. Sea water is poured into the first tank of the group, and transferred to the adjacent tank successively with the salt concentration increased, and finally the concentrated salt water sent to the other end of the tank is transferred to the roofed concentration tank.

On the other hand, the hot water and steam emitted from the well are led through the heating pipe provided in the concentration tank, and after heating and concentrating the already concentrated salt water, led into the open-air tank group. In this open-air tank group, the hot water and steam flow in the opposite direction to the flow of sea water while heating the bottom of the sea water tank and are finally released from the place of first sea water pouring tank. The salt water in the concentrating tank, concentrated by heat to the appropriate specific gravity, is further processed to remove moisture after eliminating foreign matters, and becomes a refined product.

This Saltmaking Plant formerly produced about one ton of salt daily, totalling 300 tons annually, but the annual production at present has decreased to about 150 tons due to the attenuation of the steam well.

Thus, the very primitive method of saltmaking makes the quality control and automatic control of facilities impossible with only three workers.

The Saltmaking Plant, however, filed an application to The Japan Monopoly Corporation for the construction of a large scale plant with a capacity of 100,000 tons annually. According to its plans, the company intends to drill four wells of 203 mm and about 500 m in depth, and the steam of 30 - 50 t/h per well obtained will be utilized for saltmaking and power generation. For these pruposes,

it is scheduled to construct a 7000 kW power plant and a saltmaking plant with an anuual production of 100,000 tons.

The planned salt-making plant will employ a multistage effective vacuum distillation unit used also for producing fresh water from sea water together with an ion-exchange film electrolytic dialysis unit, and the concentrated salt water obtained will be refined to be used as table-salt. A 7000 kW geothermal electric power plant will be constructed in order to integrally utilize geothermal energy and to reduce the salt-making costs. The steam required for the saltmaking and power generation will be about 70 t/h for the power generation and about 35 t/h for the vacuum distillation.

Water supply (distillation or desalination) utilizing geothermal energy in processing is under consideration in Japan. The Ikeda Geothermal Saltmaking Plant, situated near Shikabe village, Oshima Administration Area, Hokkaido, will employ a multistage-effect vacuum distillation unit used also for producing fresh water from sea water together with an ion-exchange film electrolitic dialysis unit [103].

Most of the world's desalting plants are now fueled by fossil materials. This one source of energy which has not received enough consideration despite the fact that it appears to offer great promise in certain parts of the world. This is geothermal energy which exists in some form at various locations. Presently, it is much too early to predict what the outcome will be, but those in the desalination field hope that it will lead the way to an early intimate union between geothermal energy and the desalination of water for domestic and agricultural use[209].

Medical and recreation activities in Japan have a long history of geothermal utilization. The speedy increase in utilization of geothermal resources for curing, recuperative and recreational purposes by so many people is truly a matter of surprise and probably there is no other country like Japan, where the hot springs are in

close contact with the nation. Approximately 150 million people are visiting hot springs annually. It is a large business amounting to about one billion U.S. dollars per year. Consequently, many geothermal areas are off-limits for geothermal exploration [127].

Since 1907, the method of analyzing mineral springs has been studied and discussed. The classification and efficacy have been examined by persons concerned in this field, led by the Japan Pharmaceutical Institute. On the other hand, the primitive hot spring curing method has been used from old times as a popular remedy in so-called hot water baths, and this still happens today.

It was in 1885 when the first small scale sanatorium was constructed at the Atami hot spring (Shizuoka Prefecture) as a modern hot spring curing establishment, getting rid of primitive popular curing methods. During and after the Sino-Japanese and Russo-Japanese wars, temporary military sanatoria, offering a change of air, were established at hot spring areas for the prupose of treating patients and wounded soldiers inflicted by both wars. The first permanent hot spring hospitals in Japan were the hot spring sanatoria established by the now defunct Japanese Army and Navy in 1911 and in 1923 respectively. The hot spring experimental station was first established by Kyushu University in 1931 at Beppu, and Hokkaido University and Okayama University respectively established similar stations in 1936 at Noboribetsu and in 1939 at Misasa (Tottori Pref.). The latter was used both as an experimental station and sanatorium.

Ten national hospitals were designated as hot spring curing centers at Beppu, Ito and other famous hot spring places during postwar years. Of the considerable number of hot springs distributed all over Japan, those having curing facilities at present number 25 from northern Hokkaido to southern Kyushu[103].

However, utilization of hot springs in Japan for medical treatment is very small compared to that in European countries.

In general, many areas of hot springs are health resorts, but a very small ratio is in use for medical treatment by doctors [207].

Pisciculture in Japan is considerably advanced and profitable. The Hokkaido Marine Hatching Center (Hot Water Breeding Experimental Station) has been operating since 1961 for the carrying out of various experiments, such as breeding hot water fish, fundamental test on adequate accomodation of seed fish in breeding ponds and on the kind of foodstuffs and correct quantities for feeding. In addition, studies are being made on the industrialization and profitability of fishbreeding; so far the industrialization and profitability of breeding eels have been found to be rather promising.

This experimental station uses the water from a hot spring at a temperature of 75°C containing a small quantity of salinity, which is mixed with 400 l/min of waste hot water at a temperature of 30°C from a nearby salt refining plant, and 700 l/min of water from a river nearby at temperatures of 4 - 12°C in four storage tanks and blending tanks, and is breeding eels in the tunnel ponds in hot water at the temperature of 23°C.

The eels for this experiment are purchased from Hamamatsu (Shizuoka Prefecture), from the end of March to early April as seed eels, and shipped as adult eels of 100 g-150 g in weight each after breeding from one to three years.

The following is an example of alligator raising at Atagawa Banana and the Alligator Garden, Minami-Izu-machi. The hot water source here is represented by two self-issuing wells 270 m and 290 m in depth respectively and another one at a temperature of 105°C with an output of 2000 l/min. Steam from the self-issuing wells

at 120°C is sprayed on top of a wooden box of 2 m^3 put over the well, and is separated from moisture.

Alligator raising started in 1962, and at present, alligators and crocodiles of more than 20 species are bred in the hot water at temperatures of 28 - 32°C [103].

5. Mexico

Before 1955, when exploration drilling started n Mexico, there were a number of known places with hydrothermal springs, some of which were used for recreation and bathing. However, studies before 1955 by Isita Septien (1948) and de Anda (1951 and 1953) were among the first to show the necessity of studying Mexico's geothermal resources.

The National Commission on Geothermal Energy established a department in 1955 to study possibilities and developments of the new source of geothermal energy. The reasons which prompted its creation were based on available data considered satisfactory for conducting subsurface exploration by drilling in search of natural steam for the production of electric energy.

In Mexico there are rocks from Cambrian, in Sorora, to recent. Mesozoic predominates in the central part of the country, greatly masked by acid effusive rocks. This zone and the west central zone are rich in minerls.

Figure 47 shows the approximate location of the following zones:

- Between the western part of the central portion, mentioned above, and the coastal plain of the Gulf of Mexico, there is a north-to-south

mountainous chain, intensively folded, known as the Sierra Madre Oriental. The Mexican geosyncline includes such a chain, which is formed mainly by Mesozoic, Paleozoic and Cenozoic rocks. The Sierra Madre Oriental has been subjected to an alpine type of deformation and contains limestone, shales, sandstones, conglomerates and marls. It extends from the center of Mexico to the north, comprising part of the states of Chihuahua, Tamaulipas, Nuevo Leon, Hidalgo, Coahuila and Zacatecas.

- The north and central plateaus are regions situated in the former Mexican geosyncline. They contain Paleozoic and Mesozoic rocks, which are covered in large part by volcanic flows of variable composition, from acid to basic.

- The Sierra Madre Occidental is a continuation to the south of the Basin and Range System and is formed in great part by rocks of igneous origin, both intrusive and extrusive, with greater abundance of the latter. It is believed that the predominant age of these rocks is Tertiary; their basement is unknown, but in the light of the few data available, and considering their correlation with Arizona, it is not difficult to suppose that the gross section of volcanic rocks is sublaid in large part by old terrains of Paleozoic, and even older layers. The structure which predominates in the Sierra Madre Occidental is block faulting. This wide region of the country is for the most part inaccessible, and many mineral deposits which undoubtedly are lodged in fractures have not yet been discovered

in the region. The zone, of variable width, which represents the transition between Sierra Madre Occidental and the western limit of the Mexican geosyncline, constitutes the more important mineralized region of the country, extending in the northwest to southeast direction.

- The neovolcanic zone is composed fundamentally of volcanic rocks, from Tertiary to recent age, transversal to the general trend of Sierra Madre Oriental and Sierra Madre Occidental. This is a region of intensive geyserian activity, in which the Pathe and Ixtlan fields, which are being studied, are located.

- The Baja California peninsula is formed by a batholith, mainly integrated by intrusinve igneous rocks of granitic composition, the age of which is believed to be Precretaceous. In the same part of the peninsula there are volcanic rocks from the Tertiary, located in islated basins which contain sediments from Tertiary to recent.

- The Pacific coastal plain is formed by the western slopes of the Sierra Madre Occidental; it is a zone within the limits of the continent, towards the Pacific, with intensive seismic activity, especially in the Acapulco region.

- The zones known as Sierra Madre del Sur, Sierra de Chiapas, the Gulf coastal plain and the Yucatan plateau form the remaining zones conventionally recognized in Mexico.

Schematically, Mexico exhibits a marked tilt towards the Gulf of Mexico, where recent sediments occur, whereas the Pacific coast exhibits a crystalline basement, made up of intrusive Paleozoic rocks.

Two great stresses occur in Mexico: one is projected from North America and exerts pressure towards the south, mainly along meridian 100 W; the other proceeds from South America and acts through Central America, pressing Mexico towards the northwest.

The combination of these two stresses produces an important zone of transversal dislocation, from the Gulf of Mexico to the Pacific Ocean. Such a zone is the new volcanic region, in which a basaltic plurivulcanism predominates, with intercalations of felsites, even with faneritic intrusives in dikes. It might also be considered that

Fig. 47. Physiographic zones of Mexico [211].

the Gulf of California is a consequence of this dislocation, as well as the San Andres fault zone, which reaches San Francisco, California, in the United States.

<u>Distribution of geothermal zones in Mexico</u>. To repeat, the zone of transversal dislocation known as the new volcanic region corresponds to a line of weakness in which it is supposed that the best results of geothermal energy may be encountered, not excluding the fault zone of San Adnres, which is considered a consequence of the dislocation that gave rise to the new volcanic zone (Fig. 48).

In Mexico, the presence of manifestations that might lead to obtaining steam are intimately connected, up to a certain point, with a favorable structure, mainly through fractures and zones of weakness that have constituted the conduits along which a considerable volume of volcanic materials has come to the surface. Therefore, the geothermal fields of Mexico investigated to date — Pathe, Ixtlan, Mexicali and a few others considered as potential — are found within an important structural region.

Experience gained in this field has demonstrated that calorific energy contained in steam might be utilized for industrial and economic purposes. Such energy comes from the heat accumulation of igneous rocks in the subsurface, which remain at sufficient depth to dissipate heat during a longer or shorter period of time. Fluids of meteoric character which have circulated to the depths have absorbed heat coming out at the surface as steam.

It might be thought that a certain amount of steam which appears on the surface may in fact have a magmatic origin, a matter which might better be studied by means of nuclear geochemistry through studying a good number of samples.

It is interesting to note that in the locality known as Aconchi, Sonora, there are hydrothermal manifestations with temperatures at

the surface up to 70°C. The spring deposits precipitated from such waters are highly radioactive. There is a question whether the abnormal temperature results from energy provided by the disintegration of radioactive minerals or from hot water circulating in the depths of the crust that has taken heat from an igneous body still in the process of cooling and carrying radioactive materials in solution.

Fig. 48. Location of hydrothermal springs, principal volcanos, and geothermal fields in Mexico[211].

The new volcanic zone mentioned earlier is a part of the earth's crust in which favorable structures, volcanism and steam make Mexico a zone of great interest to explore [211].

The Federal Electricity Commission is developing a second geothermal field in the Cerro Prieto area, near Mexicali, Baja California, with twenty two producing drill holles. Exploration is concentrated southeast of Cerro Prieto where hot water and steam at high temperature and pressure are present in the reservoir. To the north and south of Cerro Prieto there are three further areas of surface manifestations.

During the period from the beginning of 1968 to August 1969, the Research Institute for the Electrical Industry, a branch of the Federal Electricity Commission, has carried out geological, geophysical, and geochemical studies in four geothermal fields in the central volcanic belt, located approximately between parallels 18 and 21 north latitude, and composed of volcanic rocks of ages ranging from Tertiary to recent. All of them have very good contrast in their physiographic expression, intimately connected with active volcanic and tectonic zones of Mexico.

Apart from the Cerro Prieto field, all fields lie in the central volcanic belt of Mexico. Although they include some of the zones of strongest surface activity, they represent only a small fraction of the known thermal manifestations in this belt. These fields were selected for investigation mainly on economic grounds such as nearness to existing or projected high tension transmission lines, developing load centers, and the like.

The following descriptions of the various geothermal areas (Fig. 49) are based on a series of full exploration reports prepared for the Federal Electricity Commission of Mexico. These reports

include geological, geophysical, and geochemical survey maps as well as many tabulated data and discussions which are summarized here.

Cerro Prieto. The Cerro Prieto geothermal field is located at the northern end of the Baja California peninsula, about 30 kilometers south of the border with the United States.

The Mexicali Valley is the extension of the Imperial Valley, and retains its physiographic characteristics. It is made up of a thick deposit of delta sediments in which there are successive horizons of sands, muds, and clays with various degrees of compaction. It is terminated on the west by the Sierra Cucapah, but extending without interruption to the east to form the bed of the Colorado river.

These sediments rest uncomformably on intrusive granitic rocks, affected by the NE-SE system of faults known as the San Andres-San Jacinto. The intrusion has been intensely dislocated and fractured, allowing the steam-water mixture which supplies the wells to escape to the surface and maintain the hydrothermal activity which appears parallel to the Sierra Cucapah.

Cerro Prieto is a double volcanic crater of the Quaternary which produced basalts and pyroclastics. Close to it, to the SW, there is fumarolic and solfataric activity (boiling pools, mud volcanoes, and phreatic eruptions) on a spectacular scale. All these are aligned along a probable extension of the geothermal area in a N-S direction, while there exist new areas still not fully studied.

The structural features which affect the crystalline basement have been deduced from seismic refraction and gravity surveys, by means of which the geological structure could be determined. This

corresponds to a Cretaceous tectonic trench, rising in a series of stepped blocks towards the Sierra Cucapah to the west and descending abruptly east of Cerro Prieto where displacement of the crystalline rocks is of the order of 2900 m. However, a comparison of the detailed gravity pattern and the seismic data, bearing in mind the results of similar studies recently made in the Broadlands area of New Zealand, suggests that the effective density of the sediments in the eastern part of the area may have been increased considerably by deposition of minerals in the upper part of the hydrothermal system. Also, certain features of the seismic records from the same area would be consistent with the presence of a strongly adsorbing zone, characteristic too of the Broadlands hydrothermal system.

The first exploration drillholes were made in 1960 to depths up to 750 m. These showed a promising geothermal gradient and, after a short interruption, a more ambitious programe was undertaken which has resulted in an estimate of the steam producing potentialities of the field. In an area of 10 km^2, 42 holes have been drilled, 22 of which produce a mixture of steam and hot water. Depths range from 900 to 2000 m, and production comes from a horizon lying between 650 and 900 m, with high pressure (200 - 400 psi at the wellhead) and temperatures from 250 to 340°C.

Exploration has been concentrated in general to the SE, and it is thought that the major thermal anomaly in the area has not yet been reached. Taking into account the additional activity both to the north and south, which has not been studied at all, it is concluded that the potentialities of the field are greater than formerly believed.

Well M-3, located on top of a buried granitic block produces 200 tons per hour of steam and water from a zone 600 - 900 m deep, at a wellhead pressure of 18.8 atm (276 psi) and 210°C temperature. There is a second producing zone between 2400 and 2639 m, near the contact with the granitic basement. The characteristics of the hot fluid have improved slightly with time, with a reduction in the gas

content (CO_2, H_2S). Both temperature and pressure have remained similar after casing. It is estimated that this well can provide enough steam to generate 7600 kW. The sodium (5610 mg/l) and potassium (1040 mg/l) chlorides are in sufficient quantity to justify their economic extraction from the residual fluid.

The quantity of natural steam available has prompted the Federal Electric Commission to install a geothermal power plant, with an initial capacity of 75 MW. The calculated steam reserve volume is enough to permit this capacity to be doubled in the near future.

The operation of such a station will supplement the generating capacity of the Rosarito desalinization plant (near Tijuana) and will help reduce the growing power shortage in the Baja California region.

The operation of such a station will supplement the generating capacity of the Rosarito desalinization plant (near Tijuana) and will help reduce the growing power shortage in the Baja California region[212, 213].

However, a second set of wells is to be drilled beginning in 1972, to supply steam for a second 75 MW station. This would go on line in about 1980. A steam-powered drilling rig has been brought to Cerro Prieto, to operate on natural steam. This should have the effect of reducing drilling costs slightly. Water condensed from steam is used in construction and maintenance operations in this extremely arid region. Only a small portion of the Cerro Prieto geothermal zone has been drilled, and it is considered likely that total potential is many times that due for production in this decade. Exploration and development are carried out by an arm of the Comision Federal de Electricidad, the Mexican national electricity agency [10].

<u>Los Negritos</u>. The geothermal area of Los Negritos is located in the intersection of the western Sierra Madre and the volcanic axis, on the southeast edge of the depression known as the Chapala graben, some 120 km from the city of Guadalajara. It is a circular valley in the lowest part of the marsh some three m below the maximum

level of Lake Chapala waters, formed of lake sediments with intercalations of some tuffaceous horizons and lava flows.

Tectonically, it is affected by the major Chapala-Acambay fault system, which has produced lines of weakness from east to west, along which andesitic volcanic structures of the Tertiary age have appeared, also doslocated. Quaternary volcanic structures and an intense postvolcanic activity have greatly contributed to the formation of lakes and lagoons (Patzcuaro, Cuitzeo, etc.) and inter-mountain valleys (Jiquilpan, Ixtlan, etc.) which sometimes have a structural character.

The most recent postvolcanic activity occurred in the year 1902 when, suddenly, after a series of earthquakes, there was a violent eruption. A cloud of steam and shattered rocks rose from the central part of the valley, leaving an enormous cavity in the form of an inverted funnel. On its periphery were masses of minerals, calcite, anhydrite, travertine, chalcedony, and quartz, vesicular basalt, obsidian, and rhyolite. The crater eventually filled with meteoric water, producing the lake of La Alberca, which remains full all year round, and the Los Charales lagoon, which appears only during the rainy season, flooding the centres of thermal activity.

The activity is concentrated along two lines running roughly N-S, possibly associated with two minor faults and their intersection with a larger fault parallel to the principal system which proceeds from Sahuayo.

The thermal area consists of mud volcanoes up to 3.0 m in diameter, and dry steam fumaroles whose temperatures range from 75 to 95°C, as well as many small bubbling pools (30 - 60°C) with gas discharges consisting principally of carbon dioxide, hydrogen

sulfide, and a small proportion of methane. The phreatic level is at a depth of 1.2 m, with a recharge supplemented by runoff, which has a rate of infiltration of some 90%, flowing towards the Chapala lake.

The drainage basin includes a total area of 930 km^2, of which 705 km^2 consist of materials of volcanic origin, and 225 km^2 of lake sediments.

Resistivity surveys. The Schlumberger method was used, with the advantage that profile measurements can be made quickly, while soundings are less affected by horizontal inhomogenities.

Evidence of high temperatures at depth is found in the area around the geothermal area (Los Charales lagoon), but there is no indication of communication with the Ixtlan geothermal field. However, the possibility of communication at greater depths cannot be discounted.

Isoresistivity map is based on resistivity data from 414 measuring points, with a constant separation of 500 m between current electrodes and 50 m between potential electrodes. Topographic control is provided by a survey net covering 342 km^2.

The low resistivity area (less than 5 ohm/m) covers 40.7 km^2. It is located on lake sediments 400 to 500 m thick, and is oriented E-W, parallel to the principal fault system of the region. This low resistivity is associated with the probable existence of a thermal source at depth.

The resistivity zone included between the 5 and 10 ohm/m contours covers an area of 100.7 km^2, and extends into Lake Chapala, so that the outer (10 ohm/m) contour cannot be completed.

Electrical soundings carried out in the basin show the presence of several low resistivity layers, which descend from just below the surface near the thermal area to 65 m depth near Lake Chapala itself. Deeper layers of high resistivity may be due to basalts, or silicified zones of low porosity and permeability.

Thermal flux measurements of temperature of one m depth were made on a grid covering an area of 5.6×10^5 m^2, based on a reference point coinciding with the most conspicuous mud volcanoes (3.0 m in diameter).

These measurements were made during the dry season, when the area is accessible by vehicle or on foot. Extensive flooding occurs in the rainy season, which considerably modifies both the temperature distribution and areal extent of the thermal features.

The chemical characteristics of the hot surface discharges at Los Negritos are consistent with the presence of an upper hot water system and underlying steam reservoir which supplies the heat and some of the chemical constituents. The base temperature and pressure of the system, calculated from the $K_p = \frac{p\,CH_4}{p\,H_2}$ at the surface are, respectively, 277°C and 60 atm average while the thickness of the upper hot water system is about 750 m. The hydrothermal system appears to be self-sealing by deposition of silica and other minerals in the surface lake sediments or in the basalts immediately beneath.

Self-sealing characteristics, combined with heating from a deep lying steam reservoir would account satisfactorily both for the relatively small heat outputs of both Los Negritos and Ixtlan, and for the violent phreatic eruptions that occur from time to time. Besides the evidence of the recent eruption at Los Negritos, there

are both traditional accounts and some geological evidence of an eruption near El Salitre (Ixtlan) some hundreds of years ago, while infrared aerial surveys, and surface observation, have identified several other areas of extinct hydrothermal activity.

The power potential of a hot water system covering an area equal to that of the 5 ohm/m resistivity anomaly (40.7 km^2) and extending to a depth of 750 m is approximately 30,000 megawatt years, assuming an extraction efficiency of 25% of the theoretical yeild of mechanical energy. This would maintain a 600 megawatt generating plant for a period of 50 years, thus placing Los Negritos among the largest of known geothermal fields, possibly comparable to Larderello in Italy and The Geysers in California.

Future exploration programe. The foregoing conclusions are based solely on surface observations, and it is essential to check them throughly by a suitable exploratory drilling programe, supported where necessary by further geophysical measurements or surveys. For this purpose, five test drillholes have been sited to provide the necessary geological, petrological, geochemical and geophysical data (temperature distribution, aquifer pressure, nature of pore fluid and the like), for the next exploration stage. These new data, after correlation and possible further study, will provide the basis for decisions concerning deeper drilling and possible exploitation programes.

Ixtlan. The field of Ixtlan in the State of Michoacan near its border with the State of Jalisco, represents the extreme eastern limit of the Lake Chapala graben; it coincides with the ancient limit of the lake itself, and is situated 27 km northeast of the Los Negritos field. It is about 130 km southeast of the city of Guadalajara, and the nearest town is Zamora, 30 km to the southeast.

The intense tectonic activity to which the igneous rocks have been subjected resulted in block sinking all along the E-W fault corresponding to the principal Chapala-Acambay system. This led to the formation of structural valleys (Ixtlan, Pajacuaran, etc.) which, at the present time, are partially buried by lake sediments and a few basalt flows, with a gentle slope towards Lake Chapala.

The thermal zone is a narrow and elongated belt, extending over a length of 4 km from the village of El Salitre to the small town of Ixtlan.

Surface activity is distributed along an E-W fault at the contact between Quaternary basalt flows and the lacustrine strata of the Chapala Marsh. It takes the form of thermal springs, some intermittent or with weak geysering tendencies, with temperatures between 60 and 95°C, boiling mud (80 to 92°C), and weak emissions of steam and gas (80 to 95°C) forming warm bubbling pools. There is also a deposit of some 40 cm of geyserite along the fault. The inhabitants use the hot springs as laundries, and to cook maize, potatoes, pigs, chickens, etc. Remnants of ceramics are found embedded in the thermal deposits of the Ixtlan area, showing that the hot springs have been used since pre-Hispanic times.

The Valley of Ixtlan is drained by the Duero river, and the presence of pervious volcanic material creates geohydrological conditions maintaining two separate phreatic levels which form the recharge for the zone. The more superficial (1.2 m) is supplied from the surface waters of the river Duero, while the deeper constitutes an aquifer resulting from the structural characteristics of the valley, which allow a recharge in a NW-SE direction having direct contact with the heat source at depth. This difference of hydrostatic levels promotes a form of geyser action, many of the springs having periods of quiet and activity of fairly definite length, but changing with the seasons. Besides the natural activity, there are two wells,

nos. 1 and 2, which have continued to discharge without interruption since they were drilled some nine years ago. One of these wells exhibits a strong and well defined geyser activity.

Thermal flux survey covered a rectangle of 3.0 km^2, and the measurements were made with a bimetallic thermometer at a depth of one m.

A value of 2 X 10^3 cal/cm sec ^oC has been assumed for the mean thermal conductivity of the surface formations, which consist predominantly of lake sediments.

For resistivity survey, the Wenner system was used, with four electrodes equally spaced along a line.

An electrode spacing of 500 m (Wenner "A") was adopted for the traverses. This spacing gave minimum resistivities in most parts of the field, but it should be noted that, because of the limited size of the low resistivity area, the use of greater spacings would cause boundary effects whihc could have masked the presence of lower values at depth. These effects must also be taken into account in the interpretation of some of the soundings discussed below.

At most of the tranverse points, orthogonal cross measurements were made, and potentials taken on either side of the center point (Lee partition method) so that four values for the resistivity were available at each point. This procedure, although rather laborious, was well justified in the Ixtlan area, where very rapid lateral changes of resistivity were encountered. Therefore, detailed resistivity maps could be drawn, and these correlated extremely well both with the geochemical maps and the geological details deduced from aerial photographs and field work.

The area of low resistivity (less than 5 ohm/m) extends over the lake sediments in a low running NW-SE. Its contour is similar in

both form and position to that of the 1 m temperature anomaly, but more extensive. However, the 10 ohm/m contour takes a S-SE direction, following the minor system of faults and fractures which form a part of a graben. This evidence is also consistent with the chemical analyses of the water from the areas of El Salitre and Ixtlan which show a clear difference in their composition. Nevertheless, this difference is not necessarily conclusive evidence for the presence of two separate thermal sources, since it could be due either to more recent movement on one of the faults bounding the graben or to chemical differences in the local rock formations.

The eight soundings carried out provide the following data:

The thickness of the lake beds in the graben is of the order of 120 m resting on basalts. The lava flows to the north show a thickness of 80 to 130 m resting in their turn on lake beds, and these, finally, overlie other lava flows.

In contrast, the basalts to the SW have a thickness which varies from 200 to 300 m, alternating with lake sediments. The low resistivity layer and, consequently, the zone of higher temperatures, occurs at 90 to 160 m depth, and only in sounding no. 7 reaches 180 m.

Chemical analysis of the gases discharged from the hot pools and steam vents shows a generally high content of CO_2 and nitrogen plus inert gases, and low concentrations of H_2S, CH_4, CO, and H_2, which are the constituents most likely to have originated from a deep magma.

The thermal waters from the part of the field near Ixtlan show a uniform distribution of Cl and B, as well as of HCO_3 and SO_4, but this is not the case at El Salitre where, in contrast, the values show

much variability. The points for the Na/K ratios and the SiO_2 concentrations, plotted on a common graph, fall close to the theoretical temperature curve.

From these data, it is concluded that the maximum temperature in the upper reservoir supplying the surface thermal activity is of the order of 130 to 150°C, and that there are distinct differences in chemical behaviour between the Ixtlan and El Salitre areas. Also, the rocks forming the reservoir are andesites. It should be noted, however, that a formation identified as strongly altered basalt was found near the bottom of one of the wells, and that nearly all the surface volcanic rocks in the area have likewise been identified as basalts. Thus, the chemical evidence seems to indicate the presence of rock types not yet found by the other survey methods.

Most of the foregoing surveys and soundings were concentrated on the area of strong surface manifestations in order to determine their full extent and connection with the deeper heat sources from which they derive. Since the thickness of the lake sediments in this area is, at most, some 150 to 200 m and the maximum temperature about 150°C, the area within the 5 ohm/m contour being only some 2.3 km^2, the power potential of this upper reservoir is relatively small.

Assuming that 25% of the mechanical energy theoretically available from such a reservoir can be converted into electrical energy, the potential would be about 150 megawatt years, thus yielding ten megawatts for fifteen years. If it could be shown that the whole of the area within the ten ohm/m contour is productive, the potential would be raised to about 420 megawatt years, but this would still support only a rather small station for a limited number of years. A reservoir of this size and temperature could be exploited much more profitably as a source of industrial heat, with power production only as a possible supplementary part. Assuming the

establishment of suitable industries in the area, capable of using the heat effectively, the commercial value of the thermal energy in the Ixtlan-El Salitre reservoir, within the five ohm/m zone, is about seventeen million U.S. dollars, considering the value of heat as one U.S. dollar per million kilogram calories.

In view of the small size of the local reservoir supplying the surface activity, the resistivity survey was extended over the lake sediments to a distance of up to 5 km to the SW of Ixtlan, and over the basalts to the north. Soundings were carried out to detect a deeper heat reservoir, and the total area covered by them was about fifteen square kilometers. Low resistivity formations at greater depths were located in several of these soundings, and if these low resistivities can be shown by test drilling to be hot, a reservoir of this area would contain enough stored energy to support a 250 megawatt station for an economic period.

Test drillhole program. - On the basis of the foregoing observations and interpretation, sites have been located for five holes to depths of from 300 to 400 m, to obtain core samples and formation fluids for petrological and geochemical analyses, and to measure aquifer temperature and pressure distribution. To the south of the El Salitre area, drill hole I-3 is located inside the 3 ohm/m contour which is the level of lowest resistivity; in the course of drilling we have gone through two horizons where thermal anomalies are evident. First, one at 120 m depth, where a 90°C temperature was recorded and which showed a marked tendency to increase with depth. Second, at 577 m depth, a maximum temperature of 140°C was recorded. Here, the records show a slight increment whenever the drill hole was left idle for periods of eight hours. In this latter horizon, losses in circulation slurry have been experienced and it is possible that the drill hole is already inside the zone of high conductivity or very close to it. A core 30 cm long has been recovered. The rock sample was megascopically classified as

altered basaltic breccia, green in color, with many little quartz veins. An attempt will be made to run electrical records. As it is now evident that this is a promising well for geothermal purposes, it will continue to be drilled, probably down to 1000 m, if at all feasible.

<u>Los Humeros</u>. - This thermal area is located in the eastern part of the volcanic axis, in one of the highest sections of the eastern Sierra Madre, near the border between the States of Puebla and Veracruz. Its geographical coordinates are 97°26' west of the Greenwich meridian, and 19°40' north latitude.

It is situated within a circular structure made up of Quaternary volcanic ash formations and rhyolite domes (to the west) and these, covered by stratified deposits of volcanic ash, sands and tuffs, enclose a basin some 14 km in diameter. In this basin, an inward and poorly developed drainage system is beginning to form, with no principal drainage channel because of the rapid infiltration of the runoff. It resembles a caldera, with a level central floor. A system of open fractures has facilitated flows of viscous block lavas, which cover pumicites and other pyroclastics of high permeability, forming part of the base of the structure. In eht eastern part, a system of three N-S faults expose remains of older basalts, the thermal activity appearing in the 20 m high scarps. These faults are parallel to another regional fault which proceeds from the volcano Cofre de Perote, passes through the Cerro de Pizarro, and affects Cretaceous and Jurassic sediments to the north, after crossing the central part of the caldera.

Numerous outcrops of limestones around Los Humeros suggest that the basement must also be of this material, and it is probable that limestones at depth influence the chemical characteristics of the gases which appear at the surface.

To the east of the study area, there are many collapse craters and xalapazcos (calderas containing lakes), whose volcanic products cover older formations.

The only evidence of an abnormal heat flux consists of weak intermittent discharges of steam and hot gases which escape through fractures and fault lines, near the center of the structure. The activity heats areas up to 10 m in diameter, where the temperatures reach 90°C in small collapse basins in altered and kaolinized pumiceous sands. A few red colored patches (dry mud) contrast with the predominant white along the faults, and although the activity increases during the rainy season, there are no significant hot spring deposits. The water table is at a depth of probably 200 m, so that a strong heat flux would be required to bring hot water to the surface.

Chemical analysis of the condensate and gases suggests that the Na/K ratio, the vapour pressure, and the gas content must increase with depth. Also, that the increase in Na is due to pneumatolitic alteration of the rocks in contact with gas and steam, and that during this process K is lost by absorption or by chemical reaction, forming potash-rich silicates.

The isochloride curves show a concentration of 25 ppm and, this chloride, combined with ammonium could produce ammonium chloride, which sublimes at a low temperature. CO_2, combined with water vapor forms HCO_3 at high pressure and temperature. Its origin, is probably connected with the presence of limestones at depth. The traces of silicates (SiO_2) indicate that this rises from great depth and that, as the steam ascends, it is either deposited or exchanges as the pressure and temperature fall. Similarly, the intense thermal activity, with storage of steam, which must exist at depth, diminishes towards the surface.

Small deposits of sulfur (not in commercial quantities) and traces of elements and compounds such as hydrogen sulfide, boron and ammonium sulfate which accompany the gases are indicative of a sealed hydrothermal system with a small dissipation of heat through faults and fractures which are evidently a reflection of recent dislocations of the blocks. The heat transfer mechanism to the upper part of the phreatic water system is by thermal conduction.

The temperature survey at 1-m depth covers a minimum are of some 2 km^2, which represents only a small part of the whole thermal anomaly.

A resistivity survey will be completed shortly, and later on, an exploration program will be initiated with drillholes 20 to 30 m deep in order to establish the true boundaries of the field, which may indicate the existence of a much larger reservoir.

Los Azufres. - The area of Los Azufres is situated at 2800 m a.m.s.l. in the highest part of the western Sierra Madre, in its intersection with the western portion of the volcanic axis. The mountain of San Andres is distinguished by its rugged terrain and the vigorous cold climate begetation which fluorishes around it.

The San Andres Range runs NW-SE from Ciudad Hidalgo to lake Cuitzeo, where it ends. Along the mountain belt there are natural lagoons of varied color. Green Lagoon, in the centre of the range, and Long Lagoon of a sky blue color, make this one of the most picutresque landscapes in the State of Michoacan.

The mountain of Los Azufres is a double volcanic structure of the Tertiary, and the San Andres range as a whole originated from basaltic flows which have covered older flow rhyolites, and have themselves been overlain almost completely by recent sandy deposits. Drainage tends to be radial, and is also a reflection of the

prevailing structure. A major NW-SE fracture system runs for a distance of 18 km along the higher part of the range, and is intersected by another normal system no less important.

Many thermal features are spaced along the principal fracture, with increasing intensity in the lower parts where the range ends. Volcanos of boiling mud, fumaroles, some of them discharging high pressure, high temperature steam with a spectacular noise, large and small lagoons, and numerous zones of hydrothermal alteration, make this region one of the richest geothermal fields along the volcanic axis.

Strong discharges of hydrogen sulfide in the springs lead to the deposition of native sulfur which causes profound alteration of of the surrounding rocks; a high content of SO_4 and a low chloride content, combined with the low pH of the water and steam, cause abundant hydrothermal alteration and deposition of native sulfur from the concentrated solutions.

The low chloride content of the water suggests that the main source of heat for the surface activity could be dry or superheated steam accompanied by sulfides of hydrogen, carbon dioxide and, possibly, in the case of Pozo Maritaro, volitile boron compounds. If this were the case, part of the water discharged from the springs could be of surface origin, and a few discharges of superheated steam might be found.

In Los Azufres lagoon, the water is turbid and warmed to 35 to 38°C by constant bubbling of gas with small amounts of steam. Near one margin a hot spring erupts boiling water with a temperature of 92°C. Numerous local zones of alteration, accompanied by discharges of dry steam, have thin deposits of sulfur.

Other features of interest are:

El Chillador (The Screamer) is situated 500 m NW of the Los Azufres lagoon, and consists of several small vents with noisy discharges of dry steam, strong enough to throw up small stones. Temperatures of 105 to 110°C have been measured in openings a short distance apart, hidden by the stony ground.

Currutaco I, some 300 m from the preceding, is on the NW flank of the San Andres mountain. This is a conical structure about 20 m in diameter and 5 m high, formed by successive layers of silts. There is a continual boiling of black viscous mud in the crater, with a temperature ranging from 90 to 102°C. Other small dry steam discharges occur on its eastern border at a 92°C temperature. The mud in the crater dries out almost completely for a short period towards the end of the dry season, and tha activity consists of discharges of dry or saturated steam through many small vents. Thus, this feature also is probably fed by dry or superheated steam, the water content of the mud being due to acuumulation of rain water and condensed steam above a perched water table. Chemical action by the steam promotes soil alteration.

Currutaco II is much less spectacular that the former, and is intermittent. It also contains viscous boiling mud, with tempe rautres from 95 to 100°C, but has not formed any structure.

Pozo Maritaro, near Green Lagoon, a crater at least as spectacular as Currataco I, continually emits CO_2, H_2S, and SO_2. Steam rises to a height of 20 m, with no water discharge. Recorded surface temperatures are from 92 to 111°C. Another source nearby, called El Gallo, has similar temperatures.

Tajimaroa, some kilometers SW of the San Andres mountain, there is a lagoon within another volcanic structure where there are hot springs with acid waters. Sulfhur is deposited and exploited on a small scale.

Near Lake Cuitzeo, other manifestations of thermal activity, less spectacular but no less important from the geothermal point of view. These are known as La Tacita, Hacienda de Agua Fria, Banos del Chino, Laguna Verde, El Nopal, Cointzio, Atzimba, Araro, Zimirao, San Alejo, San Pedro, San Agustin del Maiz, Huandacareo. Puruandiro, La Piedad, and others which , at the present time, are rural spas.

The Los Azufres field and its surroundings is one of the most interesting and potentially the most important that the Research Institute for the Electrical Industry has begun to study surface geology, photointerpretation, and gas and water sampling.

La Primavera. - La Primavera is situated close to and west of the city of Guadalajara, capital of the State of Jalisco. It is described as a volcanic caldera, and the fumaroles of chief interest for geothermal investigation are located in its eastern part. The area has easy access on its northern side from the Guadalajara-Tepic highway, to the zone known by this name (La Primavera). The other, much more important zone, is known as El Colorado, and access is by way of a steep grade into the interior of the structure. The area of La Azufrera, near Tala, is also of possible geothermal interest.

Geologically, the area may be considered as a complex volcano, forming a closed basin except for a single outlet towards Tala, State of Jalisco. The formations are made up of a thick deposit of volcanic sands and tuffs, rich in volcanic glass, which cover pseudostratified rhyolitic rocks of the Tertiary. The oldest rocks are dense and fractured, with the planes of pseudostratification nearly vertical. The steam vents of the Colorado zone occur along some of these, coinciding with N-S fault scarps which bound a tectonic trench. Vent temperatures vary from 75 to 95°C, and reddish alteration zones, strongly stained by manganese, are produced. The

warm springs of the baths of La Primavera (40°C), discharging 50 to 100 liters/sec of water with a faint odour, issue from a white colored horizon of permeable material, at its contact with strongly fractured rhyolites.

The same situation occurs in the NW part, where the hot springs of Rio Caliente and Arroyo Verde originate. The waters contain considerable quantities of silica (SiO_2) and have begun to build more or less level terraces where they emerge from the rock. These springs may have a common origin with those of La Primavera and with the fumaroles of Cerro Blanco and Colorado, coming a deep heat source fed from more remote area.

Geological and photogeological maps of the area are available, and resistivity and heat flow surveys are now in progress. In addition, the following programs are contemplated:

- Sampling of the discharges, and measurements of the discharge rate and temperature at different times of the year, in order to observe the influence of meteoric water;

- Find the production base temperature of the system from existing chemical data and from the new results obtained;

- Sampling of steam and gases with the object of deducing their origin and temeperatures of formation or generation, and to locate sites for deep drill holes;

- Drill 2-inch diameter test holes to depths up to 30 m for heat flux measurement and chemical sampling in the Colorado area; and

- Undertake corrosion tests on samples of various materials exposed to steam drawn from the fumaroles[212, 213] .

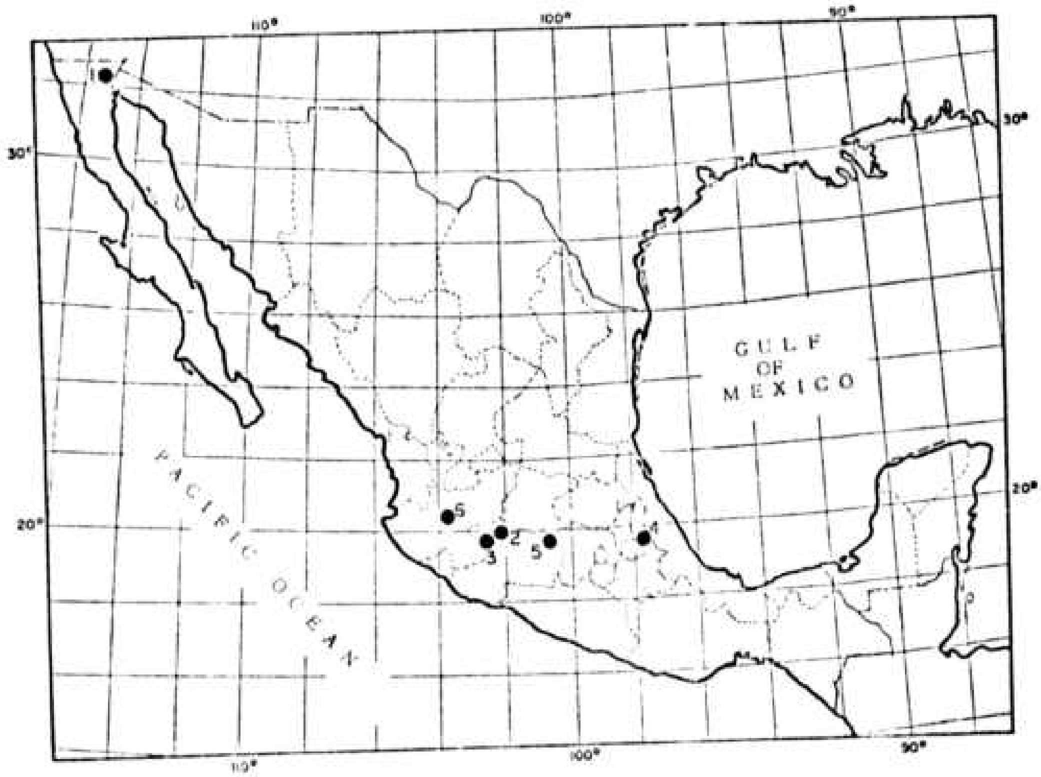


Fig. 49. Main geothermal fields of Mexico [212].

1- Cerro Prieto; 2- Ixtlan; 3- Los Negritos; 4- Los Humeros; 5- Los Azufres; 6- La Primavera.

New techniques, involving interpretation of panchromatic, ektachrome and ektachrome infrared aerographic photographs and thermographic infrared imagery recording emission from the earth's surface in middle and far infrared wavelengths (3-5μm and 8-14μm), are being introduced in geothermal investigations in Mexico to identify outstanding structural geologic features in a rapid and economical manner. The object of this work is to evaluate the new airborne infrared techniques and equipment as a complement to the data obtained from panchromatic aerial photography.

The Los Negritos-Ixtlan geothermal fields are located east of Lake Chapala at the intersection of the Sierra Madre occidental and the west-central segment of the neovolcanic axis of Mexico. The two principal zones of hydrothermal activity occur in a tectonic trench filled with lake sediments of the Quaternary intercalated with Quaternary and Holocene volcanic rocks and characterized by an intricate system of block fault tectonics, part of the Chapala-Acambay tectonic system, along which there has been volcanic activity in modern time. Surface manifestations of georhermal activity consist of relatively high heat flow and hot springs, small geysers and small steam vents aligned along an E-W axis at Ixtlan, possibly at the intersection of major fault trends and mud volcanoes and hot pools aligned NE-SW at Los Negritos.

More than 20 exit points of thermal waters are shown on infrared imagery to be aligned along an extension of the Ixtlan fault between Ixtlan and El Salitre. A narrow zone of hydrothermal alteration and deposition at the surface is identifiable on the infrared imagery of this area, closely related spatially to a resistivity low at depth. Extinct geothermal areas, near El Salitre, Ixtlan, and farther west at San Gregorio are clearly delineated on both infrared images and infrared ektachrome photographs. Predawn infrared images also show high-angle fault zones suggesting the dominance of block tectonics in much of the area. Special image

enhancement techniques applied to the original magnetic tape records will be required for more precise identification of warm ground zones and for a qualitative or semiquantitative estimate of ground radiance associated with anomalously high convective heat flow.

This project is part of the remote sensing program in which the Mexican Instituto de Investigaciones de la Industria Electrica is actively participating. The program is itself a part of a natural resources study in Mexico, carried out under the aspices of the U.S. National Aeronautics and Space Administration (NASA) in cooperation with the Mexican Comision Nacional del Espacio Exterior (CNEE) and the U.S. Geological Survey (USGS) [214].

Generation of Electric Power. - In Mexico, a 75MW geothermal power station started in 1973 at Cerro Prieto, Baja California, with several plants in experimental or planning stages.

Cerro Prieto geothermal power station, 30 km south of Mexicali on the Mexican - United States border, has a production capacity of 75MW, and is schedule for 150MW by 1980. Of 23 deep wells, 15 have been completed as production wells. Average yield is about 230,000 kg/hr of superheated brine. Approximately 20 percent flashes to steam, giving an average electric power yield of some 5MW per well, although the steam percentage varies from 13 to 25 percent in individual wells. The strongest well of the field yields nearly 700,000 kg/hr of brine, which is equivalent to 15MW of electricity. Although average well depth is about 1,500 m, one deep well reaches 2,600 m, penetrating the crystalline basement. Reservoir temperatures have been estimated to be over 300°C, with a maximum recorded temperature of 388°C. Volcanism is exhibited only locally, and the heat source is believed to be molten rock of the upper mantle, which is here at depths of about 15 to 20 km. Water in these sediments may

be derived from the ancestral Colorado river system. The reservoir fluid contains between 13,000 and 25,000 ppm total dissolved solids, mostly chlorides of sodium and calcium. Disposal of used fluid will be via ditches to the Rio Hardy, a distributary of the Colorado river, and then to the Gulf of California. Some concern, however, has been expressed over long-term consequences, and the alternatives of reinjection and ponding are under consideration. Other problems include brine corrosivity and the possibility of induced ground subsidence[10] .

The wells drilled to supply steam for the power station are distributed in a triangular arrangement to keep equal distances between them at about 650 ft. This distance was chosen at random and no critical distance has been determined as yet. Consequently, the well area is rather small.

Four main steamlines, which gather output of several wells, conduct the steam to two 37.5 MW turbine generators, manufactured by Toshiba Co. of Japan. These are single-cylinder, double-flow impuls condensing turbines, rated at 3,600 rpm. Specific steam consumption is at the rate of 16.74 lb/kwhr, or 1,256,000 lb of steam/hr at full load for the two turbines (Fig. 50).

The turbines are designed for exhaust pressure of 3.5 in hga. The turbine rotors are made of 1% chrome, 1.25% molybdenum, and 0.25% vanadium steel. The rotor blades are made of high alloy steel, 12% chrome, and the turbine casing is made of carbon steel plate.

Because of the lower cost, the high noncondensable gas content of the steam and high corrosivity of the condensed water, a spray-type condenser (similar to that used in Wairakei, New Zealand) was chosen. In this design, steam is condensed directly by circulating cooling water, and the condensate mixes with the cooling water. The

water mixed with the condensate descends through the barometric leg of the condenser to the hot well, and through concrete channels where it is pumped to the distributor in the upper part of the cooling tower. Once it is cooled, water flows to the pump pit and hence to the main condenser of each unit and other cooling services.

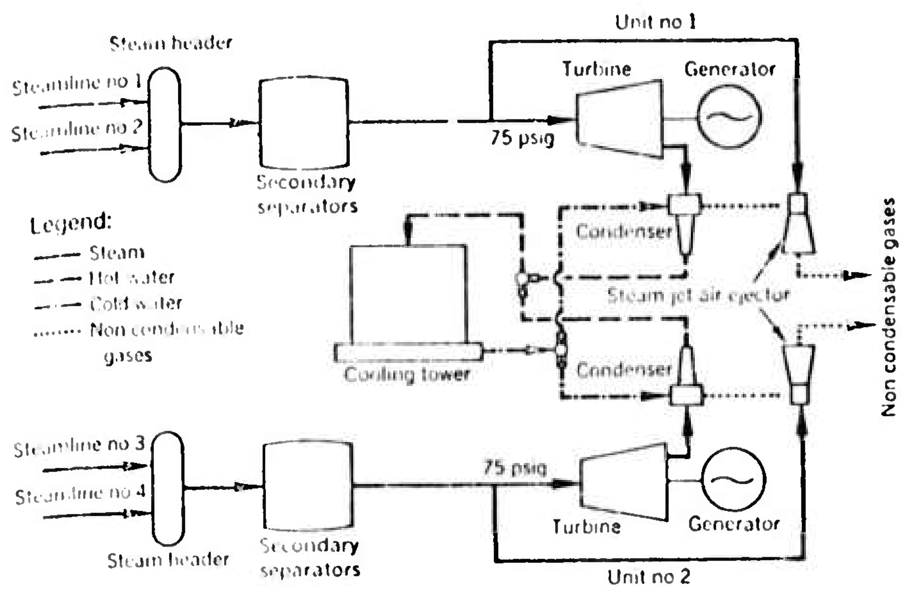


Fig. 50. Heat balance diagram of the Cerro Prieto geothermal power plant[216] .

Fig. 51 is a plan and Fig. 52 is a cross section of the Cerro Prieto geothermal power plant[122] .

A sub-station interconnects the power station with the Mexicali-Tijuana power network. The Cerro Prieto plant not only will boost the 309 MW Mexicali-Tijuana system but will also ensure power supply to Mexicali, slightly less than 20 miles from the station

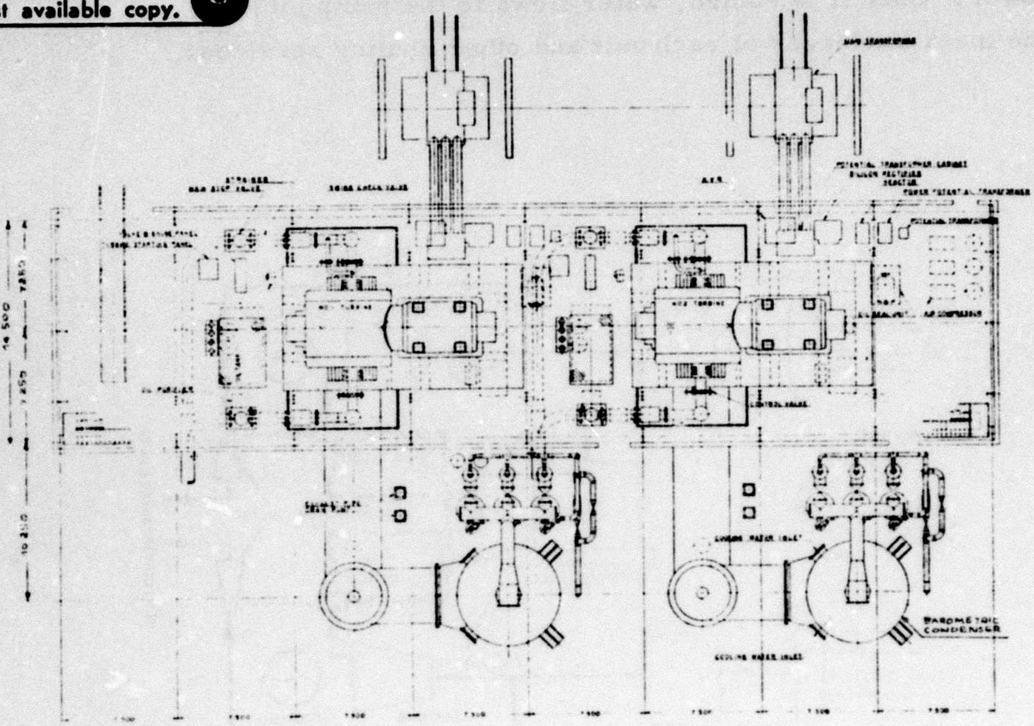


Fig. 51. General plan of Cerro Prieto geothermal power plant (dimensions in m)[122] .

In addition , this station will supplement the generating capacity of the Rosarito desalinization plant (near Tijuana) and will help reduce the growing power shortage in the Baja California region.

Furthermore, the Federal Electricity Commission (CFE) foresees, in the near future, when full development of Baja California's geothermal resources will render the operation of its thermoelectric plants unnecessary in those areas which are supplied by increasingly more expensive fuels imported from the United States [216] .

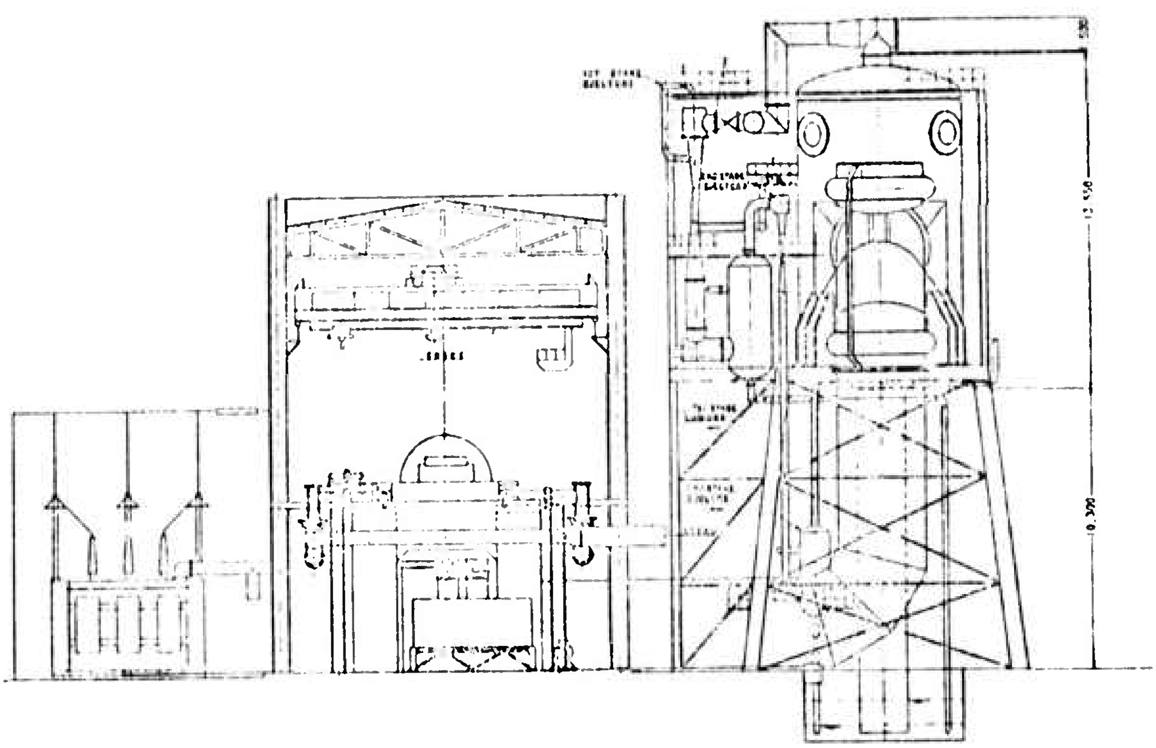


Fig. 52. Cross section of Cerro Prieto geothermal power plant (dimensions in m)[122].

Pathe geothermal power plant is situated in the State of Hidalgo, east-centeal part of Mexico (see Fig. 48). Compared with the costs of other geothermal power plants per kilowatt, it is important to note that the cost of this experimental plant is exceptionally low. The Ansaldo turbo-generator unit of 3.5MW capacity was sold by Larderello, Italy to the Comision Federal de Electricidad at a very low price, with cooperation in research work. The powerhouse and the frequency converter were recovered from old installations. The plant was put in operation in 1958, and at present, there are no planning for expansion of this plant [211].

Steam has been obtained at variable depths, due to the structural control of faults, which the wells (a total of 12) have intercepted in various zones. The zone that is probably producing consists of a more or less permeable bed of volcanic character of the Upper Tertiary, fed through fractures with steam and water [14].

Pathe geothermal field was originally chosen because it presented evidence of attractive geothermal activity, such as thermal springs and fumaroks at boiling point, a great amount of geyseritic rock, mineralized rocks with sulfides, alteration of primary rocks giving place to important deposits of caolinite, veins of gypsum and profound erosion in preferential directions with fractures. Some chemical analyses were made of the water of various springs, and it appeared opportune to start an exploratory drilling. First drilling started in August 1955. The choice of location was not based on a spring or fumarole, but rather on the position of fracture, and the possible crossing of several. For this well, percussion drill equipment was used to permit a more complete record of rocks and temperatures.

At a depth of three and a half meters, the water table was cut out, and the temperature was 28°C; at four meters the temperature rose to 40°C; and at 69 m it was 100°C, releasing the steam trapped in the mud brought out in the spoon. At a depth of 238 m the well erupted, and the temperature was around 150°C.

The temperature at the bottom of the well decreased when it reached the pyrite zone and, as it penetrated, the temperature increased abruptly. In the vicinity of the pyritic beds, the spoon brought out pieces of eroded rock, several centimeters in size, as if they had been in a surface exposed to wear produced by a strong current of water.

These facts, and the experience acquired in the perforation of other wells for the procurement of water in these places, high enough

above sea level, make it appear that the circulation of underground water is an important factor in geothermal exploitation; it acts unfavorably, by cooling and dissipating ascending thermal energy.

It has been proposed that the Pathe wells should be deepened, at least to reach the bottom near sea level to avoid the adverse effect of fast underground water currents.

After well no. 1 erupted (Fig. 53), however, eleven wells were drilled, to the north, south and east of well no. 1, at relatively shallow depths. Well no. 12 was drilled to 1,500 m in spite of the technical difficulties encountered.

There is a possibility of an underground sedimentary trap in the Pathe field. This opinion is based on the observations made on the Mesozoic limestone outcrops around Pathe, which roughly, follow a semi-ellipse. To the northwest of this locality, near Leon, such limestones are unconformably overlying crystalline schists. There are plans to conduct detailed geological surface mapping in the near future, and an electrical resistivity exploration, as well, in order properly to locate the volcanic sediments contact underneath.

In Fig. 54 is a general view of the Pathe experimental geothermal power plant of 3.5 MW capacity [211].

Fig. 53. Eruption of well no. 1 of Pathe experimental geothermal plant, Mexico[211] .

Fig. 54. General view of Pathe experimental geothermal power plant, Mexico [211].

Chemical by-products. - The Federal Electricity Commission (CFE) has been active in promoting the establishment of industrial complexes in the vicinity of Cerro Prieto which could take advantage of some of the chemical content of water, such as potassium salts and sulfur to produce pesticides, fertilizers, sulfuric acid and related by-products [216].

Considering that reservoir fluid contains between 13,000 and 25,000-ppm totally dissolved solids, mostly chlorides of sodium and calcium, there is a possibility of commercial extraction of lithium and boron [10].

Water supply (distillation or desalination). - The geothermal area of Cerro Prieto being located in one of the driest and most saline zones of Mixico, the construction of geothermal power plant

presented the problem of fresh water supply for the preparation of concrete and mortars, because the available water in the area has a salinity content between 2,000 and 3,000ppm of sodium chloride.

For this reason and because external supply was very expensive, it has been decided to use part of the steam produced by a geothermal well for the condensate, what led to design a small condensation plant (Fig. 55) able to supply the flow of 0.7 liters of water per second needed for the construction of the plant. In the future this flow will supply drinkable water for personnel and replace the water loss in the cooling system of the geothermal power plant.

The success obtained in this pilot plant presents very favorable prospects for its enlargement to meet the problem of the shortage of drinking water in the city of Mixicali.

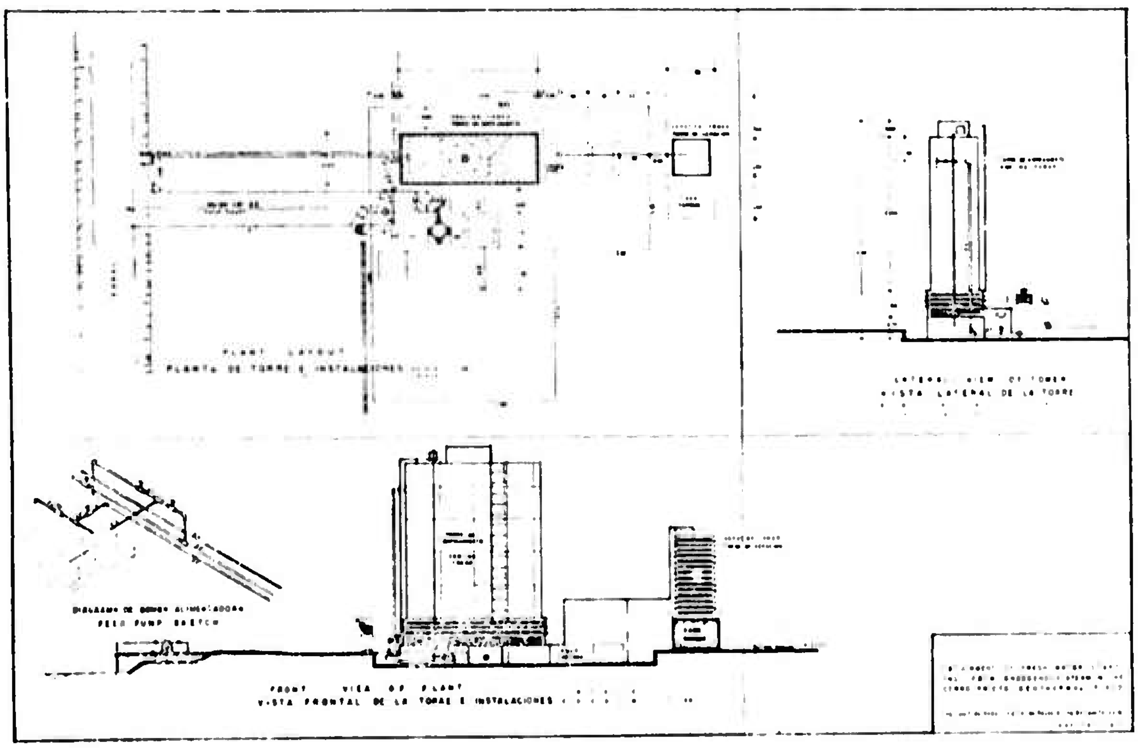


Fig. 55. Pilot plant for production of fresh water at Cerro Prieto, Mexico [217].

The condensation plant is composed of two evaporative condensers, a cooling tower, and an aeration tower. One of the principal problems was the selection of the cooling medium and the type of appropriate condensation equipment. Considering that in summer where in the Cerro Prieto area, the temperature is between 40 to 50°C, the use of air-cooled condensers was not advisable. On the other hand, the use of standard shell and tube condensers, cooling by means of the available water (3,000 - 4,000 ppm total solids) presented the problem of scaling. On account of this, it has been decided to design evaporative-type condensers by running the cooling water through the uncovered tubes, these would allow a simple and effective scale control.

The water obtained by condensation of the geothermal steam is pumped to an aeration tower for the stripping-off of the dissolved CO_2 and H_2S gases and then is pumped to the storage tank.

It is important to mention that this pilot plant is operated by the geothermal steam, and for this reason its control is very simple depending only on the control of the regulation valve of the steam fed to the system. It eliminates the use of multiple controls and allows a saving of energy and fuel consumption.

The chemical characteristics indicate that water is good for use in the construction works. However, to make this water drinkable it is necessary to add certain salts directly into the storage tank, and to eliminate the dissolved H_2S gas by filtration through activated carbon or by chlorination [217].

The Rosarito desalinization plant (near Tijuana) will obtain supplemental generating capacity from the Cerro Prieto geothermal power plant.

Medical and recreation. - There is very little information regarding utilization of geothermal waters for medical and recreational purposes. It is only mentioned, that warm springs of the baths of La Primavera with temperature of 40°C, and a discharge of 50 to 100 l/sec of water with a faint odor, issue from a white colored horizon of permeable material [212] .

In conclusion, experience obtained at Pathe, Ixtlan and Mexicali, the utilization of geothermal energy in Mexico will probably result in cheaper energy in the central and northwestern parts of the country.

Success in these three fields will encourage general enterprises in developing this new field of energy and provide economic growth of some parts of the country.

At the beginning of 1961, about 8 million pesos (about U.S. $640,000) had been invested for investigating geothermal energy in Mexico. This is, however, a small amount considering the size of the country and the possibilities offered by available geothermal resources.

6. New Zealand

The development of geothermal energy in New Zealand has been confined largely to the Taupo volcanic depression of the North Island. Utilization has centered at Wairakei, where a 160 MW power station operates; at Kawerau, where some 180,000 kg/hr of steam are used to produce newsprint and saw lumber and to generate 10 MW of electricity; and at Rotorua, where steam and hot water are used extensively for heating purposes. Natural hot water is used on a small scale at Ngawha, also on North Island, and elsewhere in the Taupo depression.

The Taupo volcanic depression extends for over 200 km in a north-northeasterly direction, parallel to the main structural grain, and culminates in the north at the active volcano White Island, in the Bay of Plenty. The zone is some 25 to 30 km broad at its widest. Fumaroles and hot springs are abundant in the central 100-km long portion of the depression. At least a dozen areas have been explored by drilling.

As a result of drilling, hot water reservoirs of sodium-chloride composition have been found, at temperatures commonly as high as 270°C, the highest being the 306° at Rotokawa. Steam is formed during the upward flow of water in wells, giving a mixture of steam and water at the wellhead. The fraction of steam varies, averaging 20 percent at Wairakei. Only rarely is dry steam produced in wells, and this is believed to reflect a flashing effect in the producing formation brought on by lowered fluid pressure near the wellbore. Gas content varies with the area. At Rotorua, hydrogen sulfide gas evolves from the superheated waters and is a nuisance and potential health hazard.

Declines in mass flow and pressure are observed commonly in wells of the Wairakei and Kawerau fields, necessitating redrilling and deepening of individual wells. These declines have also made it necessary to set intake pressures for turbines lower than was originally planned. Ground subsidence also has occurred at Wairakei. Deposition of calcite and silica, and corrosion at the points of oxidation of reservoir fluid, have created further problems in handling of the fluid. Saline effluent, representing about 80 percent of the original geothermal fluid, is disposed of to rivers, apparently without harmful effect.

Despite these problems, there was a rapid growth of interest in geothermal development through the late 1940s, culminating

in the completion of a 160 kw generating station at Wairakei. The first experimental plant had to be abandoned in 1964, after a year of operation, because of insufficient yield from wells. Subsequent construction was centralized at one facility, with extensive steam collection lines, to utilize a local river for cooling purposes. Increases in capacity were planned to 250 MW at Wairakei and to between 90 and 120 MW at the Broadlands field, just to the northeast, by 1976. But the discovery of natural gas in New Zealand changed these plans, and no geothermal power development is planned for the 1970s. However, the government is encouraging direct municipal and industrial utilization of these hot water resources.

The most significant examples of direct utilization are at Kawerau and Rotorua. The New Zealand Department of Scientific and Industiral Research and the Ministry of Works, in conjunction with the Tasman Pulp and Paper Company, began exploration at Kawerau in 1952. Over a dozen wells have since been drilled or redrilled at Kawerau, and steam from these wells is used for heat exchanging with boiler quality water for the generation of high quality steam for mill processes. Additional natural steam is used for timber drying, to operate log handling equipment, and for generation of 10MW of electricity. At Rotorua, a city of some 30,000 people, over 1,000 hot water wells supply heating to individual houses, schools, hospitals, hotels, and commercial and industrial establishments. A geothermal air conditioning scheme is in operation at a 100-room hotel at Rotorua. The construction costs were said to be as low as those of conventional cooling systems, and the operating costs are perhaps only 5 percent as high. At Rotorua, the average well depth is 100 to 150 m, with a few as deep as 250 m. Temperatures commonly are above 120°C, and reach as high as 175° at these shallow depths. When allowed to flow, these wells produce a mixture of steam, hot water above 100°, and noncondensable gases. Because of corrosion and pollution problems associated with this fluid, heat exhanging often is accomplished with municipal water,

which is circulated to consumers. Unlike the geothermal heating systems in Iceland, which are operated by the municipality, space heating in New Zealand is not operated by government agencies. It is, however, sharply regulated, especially concerning corrosion, hydrogen-sulfide emissions, disposal, contamination of other water supplies, and effects of production upon neighboring wells.

Many hot water wells in the Lake Taupo area supply heat to farms. Examples of agricultural applications include steaming of raw garbage as swill for hogs, heating of stock pens, cleaning of runs, and sterilization of various equipment. Aslo, an experimental forestry station uses steam to dry seeds and lumber, as well as to heat seed beds and buildings.

Total heat consumed for direct applications of geothermal fluid in New Zealand is probably greater than that used to generate electricity at Wairakei [10].

In general, geothermal potential for the production of electricity in New Zealand has been estimated at about 2,000 MW.

Published case histories of geothermal fields of the world are few and are generally incomplete. Perhaps the best documented geothermal case histories come from New Zealand, where many scientific studies of geothermal phenomena over the past 25 years have resulted in an impressive series of publications [15].

During the last 25 years substantial progress has been made in New Zealand in the exploitation of geothermal energy and the exploration of new fields. The greatest utilization occurs in three localities: Wairakei, Kawerau and Rotorua. In other places comparatively small scale use is made of geothermal heat. At Wairakei a geothemal power station produces 160 megawatts and at Kawerau geothermal

steam is used for processing in a pulp and paper mill and for producing a few megawatts of electric power. Utilization at Rotorua is mainly for heating. Exploration in new fields has been carried out mainly with a view to their development for electric power generation and at one field, Braodlands, a power station is programed to come into operation in 1976.

The main thermal area is in the North Island and extends in a northeasterly direction from the active volcanoes south of Lake Taupo to White Island (also active) in the Bay of Plenty. Within this zone there are several localities where hot springs, fumaroles, geysers, and abnormal earth temperature gradients occur. Where geothermal energy is produced the wells penetrate into a hot water aquifer from which steam is formed during upward flow in the wells, giving a mixture of steam and water at the wellheads. In some areas steam does exist in the formation in association with hot water but only rarely is dry steam produces.

During recent years exploration drilling has been carried out is several geothermal fields such as Broadlands, Orakeikorako, Reporoa, Rotokawa, Tauhara, Te Kopie, Waiotapu, Wairakei and Ngawha. With the exception of Ngawha in the extreme north, these areas all lie within the thermal region of the North Island (Fig. 56).

Subsequent to the initial exploration drilling at Wairakei, which culminated in developing the field for electric power production, additional wells were drilled in the outer area surrounding the main production field, such as:

Ngawha. - A geothermal power station at Ngawha would be beneficial as no other natural resources for electric power development are available in this region. One well was drilled but the results obtained did not favor continuing with further exploration. The bottom

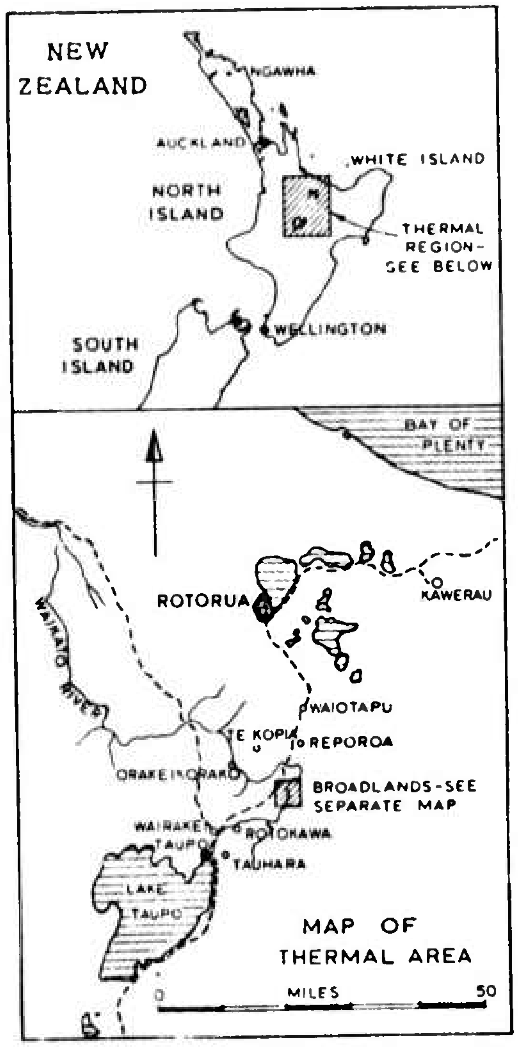


Fig. 56. Geothermal areas of North Island, New Zealand [102].

hole temperatures of 236°C was fairly satisfactory but significantly less than had been measured in other areas. Also the output from the well was very small and contained a high proportion of gas. Although drilling revealed a thick impermeable cap, probably of wide extent, the producing formation was of low permeability with only a small prospect of penetrating into permeable rocks in the argillite below 1750 feet.

Orakeikorako. - Of the four wells drilled two had satisfactory temperatures but only one produced a significant quantity of steam. The steam/water ratio is rather low. The temperature graphs indicate low temperatures for a considerable depth below the surface and it is likely that surface waters percolate downwards and dilute the hot flow from depth. Low chloride content of the well discharge reinforces this belief.

Rotokawa. - High temperatures were found in the two wells drilled at Rotokawa, 306°C measured in a well being the highest yet measured in a geothermal well anywhere in New Zealand. The outputs from two wells are generally similar and the proportion of steam is high. The gas content is fairly high and the formation is only moderately permeable.

Incidentally, sulfur was mined from surface deposits in the Rotokawa locality in years gone by but output was never very high. More recently a private company has completed preliminary shallow drilling of the deposit and feasibility and economic studies are being made. The richest deposit, averaging 20% sulfur, occurs in a bed 100 ft or more in thickness beneath about 100 ft of overburden and it has been reported that it might contain in excess of six million tons of sulfhur. As parts of the area extend into hot ground the mining procedure would have to be undertaken with due care but if it eventuates it is likely that geothermal steam would be used for processing the ore.

Reporoa. - The only well drilled at Reporoa, revealed indifferent temperature and low permeability,but does not discharge satisfactorily.

Tauhara. - The Tauhara field is adjacent to the Wairakei field and encroaches into the township of Taupo. Cores obtained from the four wells drilled indicate that the geological formations are similar to those existing at Wairakei and underground temperatures are comparable with those initially measured in Wairakei wells.

Aquifer pressure in the Tauhara field is about 100 psi higher than that generally occurring in the Wairakei field at corresponding deep levels. At Wairakei the aquifer pressure has declined considerably during the years of exploitation but the rate of decline is now very slow. Aquifer pressure at Tauhara is also declining, but at a rate very much less than at Wairakei, even when all the wells at Tauhara have been kept shut for a long time. The relationship between the two fields is still under observation but it appears that there is a weak linkage between them. It does seem, however, that exploitation at Tauhara would not significantly affect productivity of the wells at Wairakei.

Te Kopia. - The Te Kopia area is adjacent to Orakeikorako and is characterized by thermal activity on a well difined fault scarp. Of the two wells drilled only one was successful, giving a moderate output of steam but wiht a high proportion of water. In both wells the highest temperatures occur in upper formations and are fairly good but at depth they are indifferent. Slickensided cores or cores intensely crushed and brecciated obtained during the drilling of both wells indicated that they has penetrated fault zones below the depth of the production casing.

In these fields more exploration drilling is necessary before any of them can be adequately appraised for possible exploitation. The program was planned to obtain information about each field, and

to select the most promising for further drilling. The ultimate choice was between the Tauhara and Broadlands fields. The latter was selected and during 1967 drilling activities were concentrated there.

Broadlands. - The Broadlands locality was chosen for exploration drilling as the result of a regional resistivity survey. Previously it had not been rated very highly as natural thermal activity is much less than occurs in many other thermal areas. The first few wells indicated high temperatures and exceptionally good production was obtained from some of them. By the end of September 1969 sixteen wells had been completed and examination of cores and cuttings from the wells has enabled geological structure to be fairly well determined. In general, good production is obtained between 1500 and 2500 depth but most wells have been drilled deeper to obtain geological information and temperatures at depths [102].

Geothermal investigation drilling started at Broadlands in 1965, and at the cessation of operations in 1971, a total of 25 wells and been completed. The total output from the wells so far drilled is sufficient to generate approximately 120 MW. Insufficient drilling has been done to estimate the ultimate capacity, but there is little doubt that the field could support it equivalent to at least 180 MW.

The field is accessible by road, being 35 miles from the city of Rotorua on State Highway No. 5. The nearest railhead is Rotorua, and the nearest overseas port Tauranga, approximately 85 miles away by road. The field is located in gently rolling or almost level, sparsely populated farming and forest country. The Waikato River, having a mean flow at Broadlands of 4800 cusecs, divides the field in two [98].

Broadlands geothermal field is underlain by a stratified acid volcanic sequence of Quaternary age resting unconformably on early Mesozoic or late Paleozoic indurated quartzose feldspathic sandstone and argilite, commonly referred to as the greywacke basement. The surface of the basement slopes westward from 500-1000 ft above sea level on the Kaingaroa plateau to 7000-8000 ft below sea level in the Taupo-Reporoa basin.

Bouguer negative gravity anomalies increase steadily from east to west across the field marking the descent of the basement. Major buried fault block structures (horsts) interrupting the steady westward descent of the basement, are associated with major thermal anomalies with temperatures exceeding 300°C. Wedges of clastic greywacke derived sediments (Waikora formation) thin westward from buried basement scarps and interdigitate with pumiceous sediments and pyroclastics of the Ohakuri group. Five important confining layers are marked by two extensive rhyolitic flow units, and three thick ignimbritic ash flow units. These separate four aquifers - the Waiora, Rautawiri, upper Ohakuri, and lower Ohakuri - which progressively decrease in permeability with depth.

Steam production has so far been obtained from the Waiora and Rautawiri aquifers in the Ohaki production area west of the Waikato river. Productive drillholes are sited along faults transecting rhyolite dome which caps the Waiora aquifer. About 1000 klb/hr of high-pressure (200 psi) steam has been proved by 12 drillholes, equivalent to 80 MW of generated power. Steam production east of the Waikato river is negligible except for a small and unreliable flow of almost dry steam from fractured rhyolite on the crest of a horst in basement rocks [219].

In carrying out the drilling program wells have been sited to determine the lateral extent of the field and also to test productivity in the better localities, particularly in the northwest where several faults occur. Unlike the Wairakei field where lateral permeability is high the formations at Broadlands are mcuh less permeable and productivity is largely dependent on intersecting faults or fissures.

This was particularly evident from the first well drilled which did not yield satisfactorily despite high temperatures. In an attempt to improve its performance by breaking out the formation the slotted liner was remeoved and the well blown vertically on several occasions. The ejection of several hundred cubic yards of rock undoubtedly enlarged the borehole cavity but without improvement in productivity.

Except for the marginal wells in the southwest, the maximum temperatures are 270°C or more and the temperature gradients indicate the likelihood of higher temperatures below the depth drilled. However, the maximum recorded temperature in a completed well is 295°C during a temporary cessation of drilling at 6,400 feet [102] .

Kawerau. - Kawerau geothermal field, 60 miles northeast of Wairakei, has been drilled by twelve investigation wells. A reasonably deep pumice breccia aquifer was drilled (1,500 - 2,400 feet), capped by thick rhyolite flows. Performance of the wells was initially good, corresponding to average Wairakei production, but most of the wells downgraded after three years' production, owing to recharge by cooler water from the east and southeast. Recently two of the wells were deepened to over 3,000 feet and penetrated andesites (2,400 - 2,700 feet), similar to those at Wairakei and Waiotapu, underlain by dense ignimbrites. The andesites are extensively fissured; temperatures are high (270°C+) and both wells are now producing at high pressure, giving results equivalent to the best of the Wairakei wells. The relation of the andesite aquifer to the overlying pumice breccia aquifer is at present not certain although in one of the wells it appears to be capped by mudstones. The future behavior of the andesite aquifer is difficult to forecast and largely depends on how effectively it is capped and thus insulated from the overlying aquifer into which cooler water has already penetrated. Comparison with Wairakei would suggest that the thick andesites encountered in these two holes indicate proximity to the heat source and are thus a favorable indication that high pressure

production may be maintained over a reasonable period. The Kawerau thermal area is crossed by numerous active faults but these are located a mile to the west of the drilled part of the field. The drilled area is covered by recent alluvium, and faults, if present, are likely to be buried and invisible at the surface [54].

The possibility of using geothermal steam in a projected pulp and paper mill was the main reason for undertaking geothermal exploration at Kawerau early in 1952. Although there was a choice of localities, Kawerau offered the advantage of a natural source of steam if it could be produced economically. At that time exploration drilling at Wairakei had been going on for two years or more with promising results which gave encouragement to commence drilling at Kawerau. In the outcome this locality was finally chosen for the mill site (Fig. 57).

For some years good use has been made of geothermal steam by the Tasman Pulp and Paper Company who operate the mills which produce newsprint, kraft pulp and sawn timber. Nearly 400,000 lb/hr of geothermal steam is used for processing and generating a small amount of electric power, and , in addition, conventional boilers burning black liquor, wood waste, and coal or oil supply 350,000 lb/hr at 650 psig and 750°F.

Geothermal steam is delivered to the mills at pressures of 100 psig and 200 psig. The wells produce a mixture of steam and water of enthalpy varying between 430 and 624 BTU/lb, the steam being separated in conventional cyclone separators. In addition,steam at 100 psig is flashed from the water separated at 200 psig.

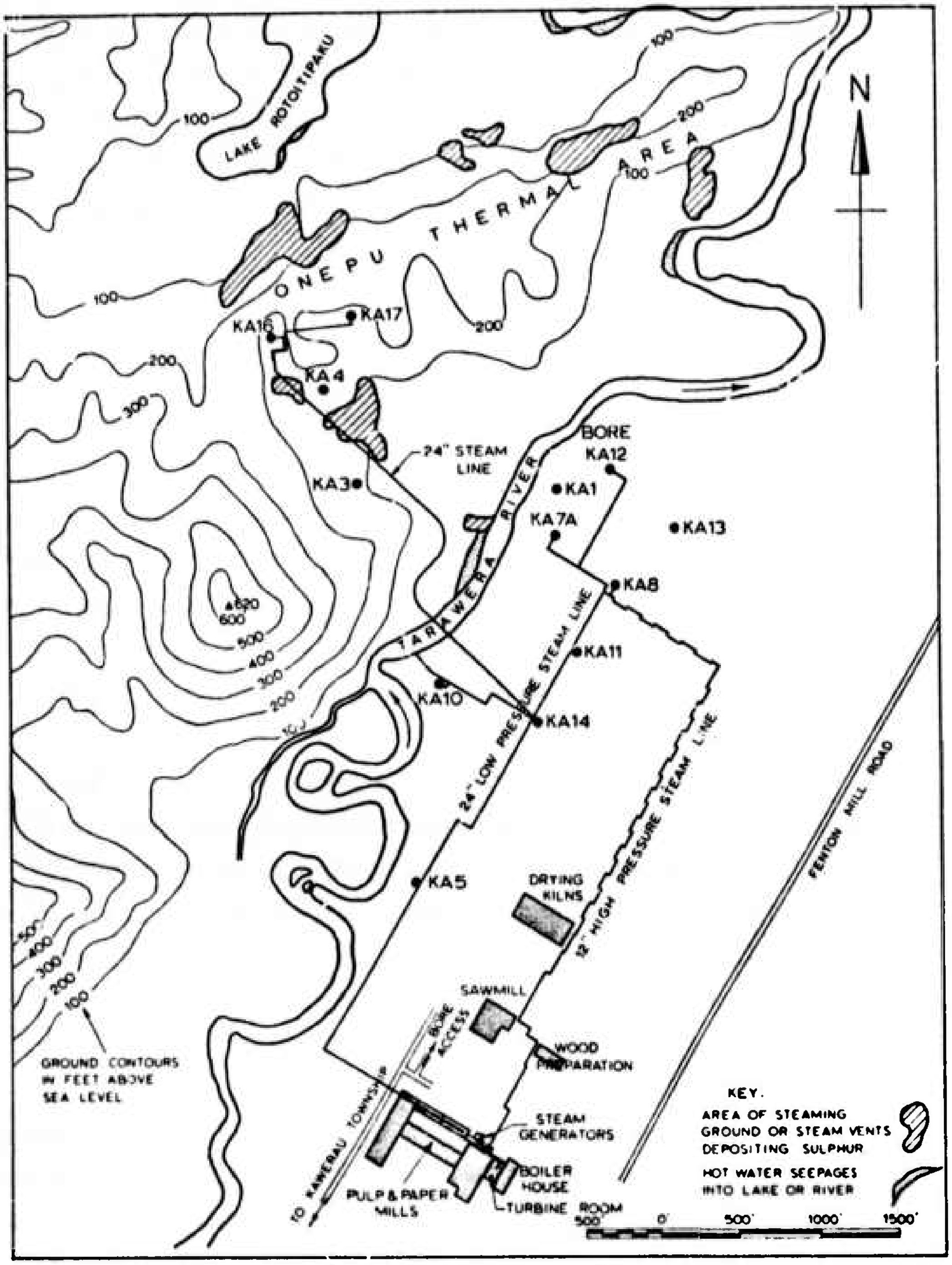


Fig. 57. Kawerau geothermal power plant, New Zealand [102].

The geothermal steam contains about 2 1/2% by weight of noncondensable gases about 91% of which is carbon dioxide and the remainder mostly hydrogen sulfide. No trouble has been experienced with corrosion in the absence of oxygen and carbon steels have proved satisfactory, but such items as glands, gland studs, valve seats and spindles are usually made from stainless steels.

Two steam generators are installed producing clean steam which is fed into the service mains to supplement boiler steam. Geothermal steam is passed through heating coils in the steam generators one of which produces 55,000 lb/hr of clean steam at 150 psig and the other 45,000 lb/hr at 50 psig. Feed water for these units is pumped from the boiler plant hot well through feed water heaters where it is heated by the geothermal condensate before entering the generator vessels.

In addition to generating clean steam required for mill processes, geothermal steam is used direct. Such applications include timber drying, log handling equipment, recovery boiler shatter sprays and liquor heaters, and electric power generation.

Geothermal steam surplus to mill requirements is fed at 100 psig to a 10 MW noncondensing turbo alternator exhausting to atmosphere. Up to 100,000 lb/hr of the exhaust steam is fed to a black liquor pre-evaporator where it is condensed. This turbo alternator operates in parallel with other units fed with boiler steam and with the external power supply. If the latter fails the geothermal turbine takes preference in the demand for steam. To generate its full rated output it requires 319,000 lb/hr of steam.

Undoubtedly geothermal heat can be used more efficiently for heating purposes than for electric power generation and the

utilization at Kawerau is a good example. The full potential of the area remains to be determined when justified economically. It is possible, however, that full use of the outputs from wells can be made by transmitting through the existing 24 in pipeline both water and steam to separators located near the eastern end of the line. The pipeline has been designed with this purpose in view and is suitable for a pressure of 300 psig. The wells would operate at a pressure higher than at present and low pressure steam flashed from the separated hot water would significantly increase the availability of steam. The outcome will depend on tests yet to be done to determine the practicability of transmitting the steam and water mixture [102].

Waiotapu. - Waiotapu geothermal field, 30 miles northeast of Wairakei has been drilled by seven investigation wells. The rock sequence penetrated is similar to that at Wairakei except that the ignimbrites are closer to surface and the overlying aquifer is thin (less than 1,000 feet) and useless for high pressure steam production. A deeper aquifer was drilled within the ignimbrite sequence by three wells and proved initially promising, the three holes giving results comparable with average Wairakei wells. However, mineral deposition, principally calcite, rapidly downgrades the wells to within a few months. The deep aquifer is also thin (200-400 feet) and not greatly permeable due to hydrothermal rock alteration. No fissure zones were drilled, although holes were sited adjacent to fault traces visible on air photographs. A pattern of intersecting faults similar to Wairakei was noted in the undrilled southern part of the field and may yet prove to be the source area for the hydrothermal water. Andesite flows similar to those at Wairakei were encountered within the ignimbrite sequence in the three deep wells and thicken south towards the supposed source area in the southern part of the field. Maximum temperatures increase south

also from 270°C to over 290°C. This may mean that volcanism and heat flow are related to the same structural conditions as they are at Wairakei and should prove a useful guide to the search for high pressure steam when the thermal area is again drilled [54].

The hot water reservoir above the main ignimbrite sheet has only a very weak cap, and there is consequently little pressure differential to produce strongly flowing bores. The high temperature reservoir below the Waiotapu ignimbrite has a strong impermeable cap and produces acceptable quantities of steam from the relatively impermeable formations so far found only in three holes drilled into it [53].

Geophysical prospecting. - Hydrothermal fields differ so greatly in character and environment that geophysical methods meet with varying success in prospecting for steam or hot water. In some cases there is difficulty in applying geophysical techniques and in others there is difficulty in interpretation.

Owing to the permeability of the rocks, most New Zealand fields yield wet steam and little work has been done on dry steam fields. The permeability of the rocks also results in usable hot water being often found by drilling close to the hot springs or fumaroles, so that much small scale exploitation has been possible without the help of prospecting. Geophysics has been employed in mapping the limits of such fields, but its main uses have been in the study of the geological background, or in the attempt to penetrate beneath the shallow reservoir to locate deeper aquifers or feed channels.

Gravity surveys are primarily used to indicate the basement structure and are not very detailed, but minor positive anomalies have been found, coinciding with some fields, which probably indicate intrusive rocks genetically associated with the hot water.

The basement rocks are only weakly magnetized, and magnetic surveys therefore indicate the distribution of magnetic rocks within the overburden. Detailed surveys are of value, since hydrothermal alteration converts the magnetite in the rocks to pyrite, thus weakening the magnetic field. This has enabled useful deductions to be made about the source of the Wairakei hot water.

Resistivity surveys, designed to map the distribution of hot water at the water table, have been successful in uniform geological conditions, but the interpretation is liable to be complicated by porosity and salinity variations. Deep penetration is hampered by the shielding effect of hot water near the surface.

Seismic refraction surveys have located cap rocks in some fields. Reflection work at Wairakei showed very low seismic velocities, suggesting steam in the rocks in place of water, and dry steam has since been tapped in this area. Seismic work in hydrothermal fields is handicapped by very high natural noise levels and energy dissipation.

Early attempts at well logging showed promise of locating producing horizons by comparing natural potential logs run under standing and flowing conditions. Similar work on deeper and hotter holes is prevented by the inability of insulated cables to withstand the physical and chemical conditions in geothermal drillholes [22].

Electromagnetic surveys using the horizontal coplanar loop technique in the Broadlands field, New Zealand, have provided information on resistivities to a depth of about 30 meters. The survey at Broadlands was largely experimental, which had proved satisfactory in in New Zealand. The principal advantages of the electromagnetic method lie in its high speed and low cost, which make it an attractive alternative to direct temperature surveys.

In-phase and quadrature components at each of two frequencies were observed at field stations, giving four estimates of resistivity. These have been combined in the construction of the resistivity maps. In reducing the data it has been assumed that the ground resistivity is uniform down to the depth of maximum penetration.

Within the limits set by volume considerations there is good correlation between resistivity down to 30 meters and temperatures measured at half this depth [164].

<u>Geochemical investigation</u>. From experience with the hydrothermal areas of New Zealand, the chemical work which would be helpful during prospecting is very important for evaluation of various areas. For Wairakei and Waiotapu geothermal fields, the chemistry of the discharges from prospecting drillholes is compared with that of the waters from natural springs in the area.

For Wairakei, the chemical analyses of steam and water from about sixty deep production holes are used to derive patterns of water and steam movement. From this type of information, improved positions for future drillholes can be selected.

Ratios of ions, such as Na/K, Na/Rb, Na/Ca, are useful indicators of water movement, while the composition (CO_2, H_2S, NH_3) and content of gas in the steam give details on conditions of steam separation from hot water.

A measure of the tendency of silica and calcite to precipitate from solution in bore pipes can be obtained from published solubility information, together with the contents of silica, or of calcium and bicarbonate, in the waters, and of carbon dioxide in the complete bore discharge.

The chemical work on geothermal drillholes in New Zealand has been limited to hydrothermal systems with heat stored in permeable strata as high temperature (200-280°C) chloride water. In the three New Zealand areas where deep drilling has been carried out (Wairakei, Waiotapu, and Kawerau), water was found at maximum temperatures ranging from 265° to 295°C, containing in solution about 0.3 percent sodium chloride, and silica and calcium carbonate close to saturation.

Hydrothermal systems of this type are common to many parts of the world (Japan, Kamchatka, Iceland, Italy), and an examination of the techniques and results of drillhole sampling in New Zealand may be of assistance to other countries.

The waters at Waiotapu and Wairakei are similar in general character, the Waiotapu waters being more dilute. The ratios of Na/Li and Cl/B, and the bicarbonate concentrations, are higher at Waiotapu, though the Cl/Br ratios are rather lower.

Kawerau waters are notably low in calcium concentrations and in Cl/B ratios. The concentrations of bicarbonate are much higher than in the other two areas.

The pH values for atmospheric pressure separation are similar for all three areas. The addition of a steam phase containing carbon dioxide to re-form the original deep water at about 250° results in a solution slightly more acid than neutral water for the temperature [220].

Sampling of gas from fumaroles and pools can also be useful. Low gas content of the steam in large fumaroles, and large variations in the gas content, and in the ratios CO_2/H_2S and CO_2/NH_3, are an indication that steam is boiling off from underlying chloride water.

Experience at Wairakei indicates that the values of the consittuent ratios Cl/B, Cl/F, Cl/As, Cl/Br, Cl/SO_4, Na/Li are the same in the spring waters as in the underground source of chloride water. From the study of other active areas, it is concluded that a thermal area often has characteristic ratios, constant in that area, but very different from those of other areas. The values of the ratios Cl/As, Na/Li, Na/Cs for all the areas of a region are useful in judging the uniformity of the magma, in detecting areas belonging to an older period of activity, and in comparing the region with others in the world. In choosing any one area for the first prospecting by drilling, the most favorable chemical indication for a large uniform supply of hot water would be a general similarity to Wairakei in chloride content, and in the ratios Cl/B, Cl/F, Cl/SO_4. Areas with more than one set of constituent ratios, should initially be avoided, also areas with low Cl/SO_4 ratios. Low Na/K ratios should be a favorable indication for locating bores near feeding fissures. Progress in prospecting drilling is followed at first by comparison of the values for the bore waters with those for the natural waters [221].

In samples of condensate and gas, from fumaroles or separated steam, hydrogen sulfide and carbon dioxide are determined in an alkaline extract, the first by titration with iodine and thiosulfate, the second by titration with acid. Oxygen, hydrogen, hydrocarbons and nitrogen are determined by a constant volume gas analysis method. In a second sample, fluoride is titrated directly with thorium; boric acid is titrated with alkali, using mannitol; and ammonia is determined photometrically with phenate. In the prospecting stage field sampling trips were made from Wellington; later a field laboratory was set up at Wairakei [224].

Representative sampling of steam and water discharging from a drillhole is not simple, as the pipe contains a rapidly flowing mixture in which the volume ratio, steam/water, may be several hundred to one. Separate steam and water samples are necessary, and analyses are combined to give results for the complete discharge from a knowledge of its dryness fraction.

Sampling methods depend on the arrangement of the wellhead and by-pass of a drillhole, as changes occur between the time the hole is first opened to the time it reaches the production stage.

The requirements of adequate sampling are examined in the light of the flow patterns which have been found to exist in the horizontal discharge pipes at Wairakei. Errors may occur when steam and water are not sampled in the same proportion that exists in the pipe at the sampling pressure.

Steam samples are condensed in water-cooled glass flasks of several litres capacity, and are analysed for their gas contents, as well as for the dissolved constituents, ammonia, boric acid, fluoride and chloride. Several water samples are collected for specific estimations such as major ionic constituents, trace metals, isotope ratios, and pH and dissolved gas determinations [223].

Isotope work in New Zealand has concentrated largely on the radioactive carbon-14 isotope and on the stable isotopes of carbon and sulfur. More recently, measurements of natural tritium and deuterium have been made.

The most promising application of the stable carbon-13 isotope has been in the estimation of underground temperatures from the isotopic equilibrium between the carbon atoms of carbon dioxide and methane. Temperatures calculated by this method have been found in good agreement with the bottom of the bore trmperaturds (about 250^{o}) at Wairakei and with the vent temperature (450^{o}C) of a fumarole measured on White Island. The isotopic exchange is thought to proceed via the reaction with hydrogen and water, i.e.,

$$CO_2 + 4\,H_2 \rightleftarrows CH^4 + 2\,H_2O$$

Analyses of bore gases indicate that this reaction is close to chemical equilibrium.

Measurements of S^{32}/S^{34} sulfur isotopic ratios were made for steam and water phases of bore discharges.

Studies of water circulation times, which are important as an indication of the water storage, have been undertaken using natural tri um and carbon-14. The tritium activity obtained indicates an age of less than fifty years if there is a single circulation path. It is possible, however, that there are several circulation paths and the tritium activity may be due to dilution by shallower groundwater of much younger age.

The carbon-14 isotope (5,760 years half life) is useful for much longer circulation times, but the results are complicated by the addition of old carbon dioxide to the system underground. Production bores sampled at Wairakei had C^{14} activities of 1/2 to 1 percent of atmospheric. Measurements of argon concentration have been made as a possible means of estimating this dilution.

Nautral deuterium measurements have been made as the first step in obtaining H/D v O^{16}/O^{18} graphs. The variation of H/D has been found to be rather small, about 5 percent [222].

Generation of electric power.

Wairakei geothermal power plant, the second largest plant in the world with a capacity of over 192.6 MW, was put into operation in 1958 (Fig. 58, 59, 60, 61). Exploratory drilling began early in 1950, and after two years, 15 wells have been drilled to a depth between 560 and 1,000 ft with promising results. It was then decided to continue exploratory drilling to prove availability of steam from such depth for a 20 MW (or more) power station; five more wells were drilled during the next year. This drilling revealed higher temperatures at depth (250°C) and productivity was so good that four more wells (8 inches in diameter) at a depth of 1,200 to 4,000 ft were drilled in the same general area, with six more smaller-diameter wells in more remote locations to widen the area explored.

Early in 1954 it was apparent that the field could be developed for an additional 20 MW.

During 1954, the New Zealand government and the U.K. Atomic Energy Authority became interested in a joint project to produce heavy water at Wairakei in conjunction with 47 MW of electric power. Early in 1956, however, the U.K.A.E.A. withdrew and heavy water production was abandoned.

The project was constructed in two main stages, as overall planning provided for a possible further development of 90 MW by using steam flashed from the hot water.

In summary the total installed capacity is:

"A" Station --- 102.6 MW capacity comprising of:

2 HP* units of 6.5 MW each,

2 HP units of 11.2 MW each,

2 IP* units of 11.2 MW each,

4 LP* units of 11.2 MW each.

"B" Station --- 90 MW capacity comprising of:

3 MP* units of 30.0 MW each.

One 11.2-MW HP unit and one 30-MW unit were initially installed as a standby plant to use additional steam should it become available. However, full loading of all units has never been achieved, the maximum net station output having been 173 MW limited to steam supply [225].

Fig. 58. shows the general outlay of the Wairakei geothermal field with power station "A" and "B" and pertinant components [229].

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* HP = high pressure

* IP = intermediate pressure

* LP = low pressure

* MP = mixed pressure

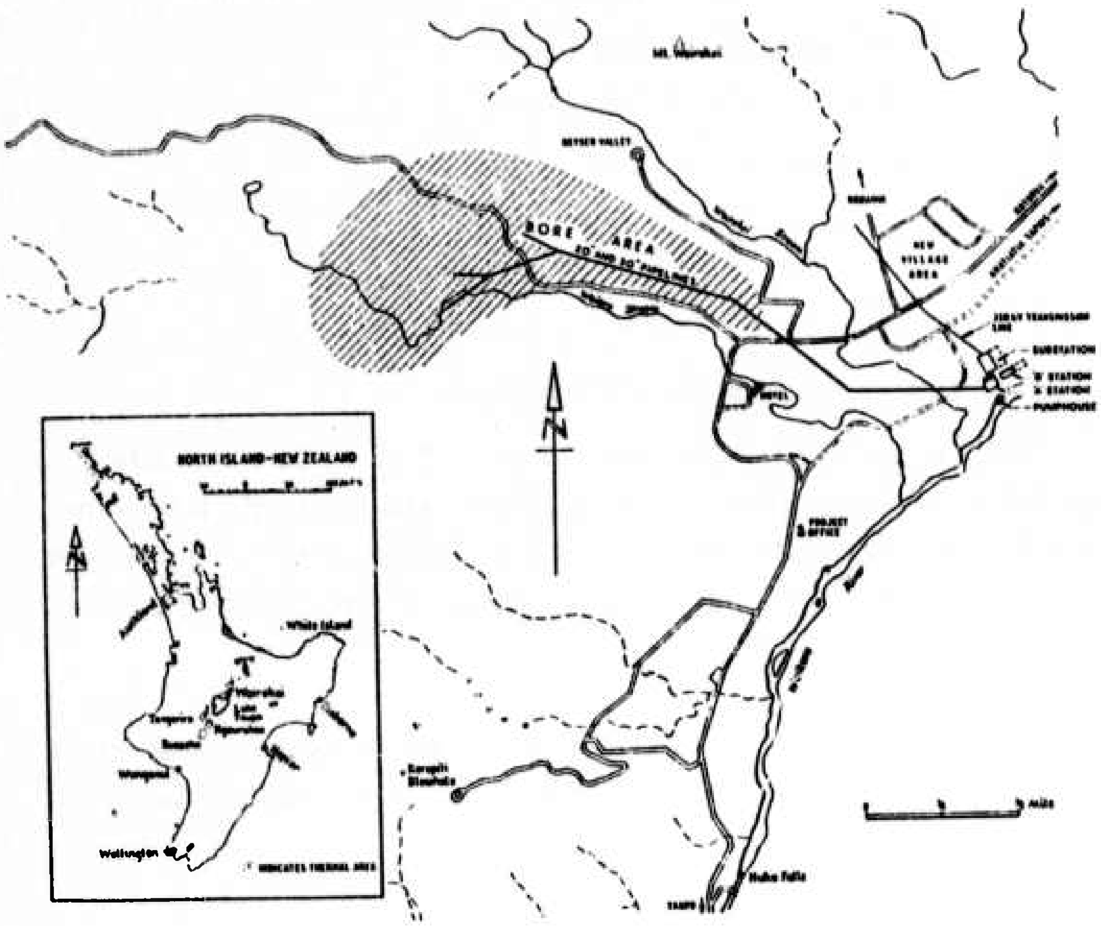

Fig. 58. Wairakei geothermal field with power stations "A" and "B" [229].

However, there is a possible future extension by 3MP sets at 30MW each, bringing planned ultimate development to 282.2MW capacity [229].

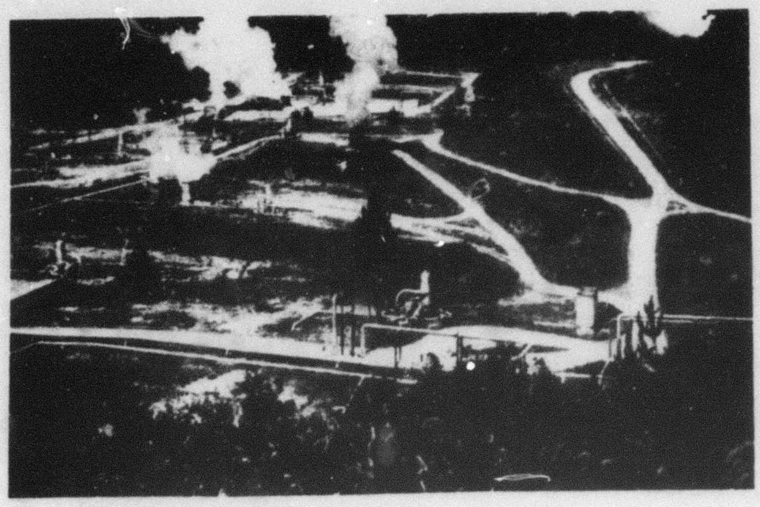

Fig. 59. Wairakei geothermal power plant, New Zealand [227].

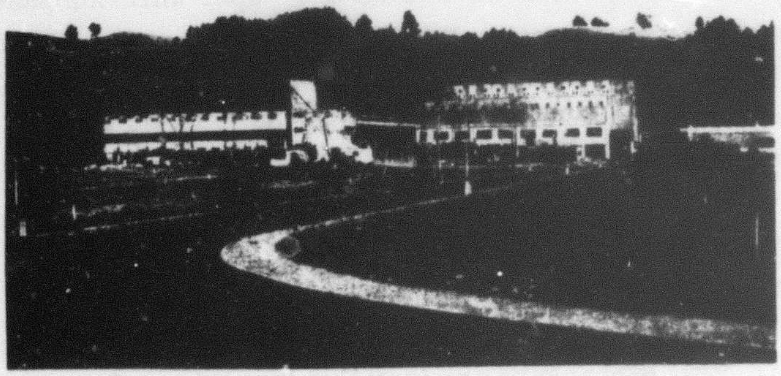

Fig. 60. Wairakei geothermal generating station, switchyard and transmission towers, New Zealand [227].

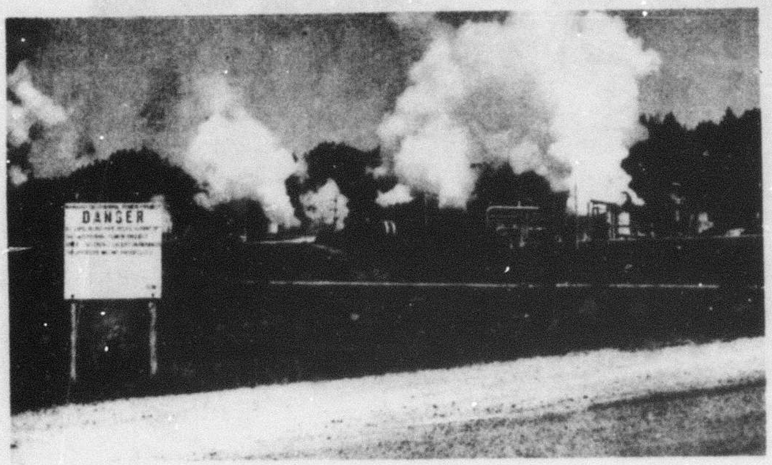

Fig. 6[illegible] General view of Wairakei geothermal power plant, New Zealand [227].

Kawerau geothermal power plant (Fig. 57) was put into operation in 1961 by the Tasman Pulp and Paper Mill Company which produces newsprint, pulp (using the Kraft process), and saw timber. The mills have been erected close to the source of geothermal energy at the Tarawera river. Nearly 400,000 lb/hr of geothermal steam is used for processing and generating electric power. Power plant has an installed capacity (1972) of 10 MW, and is generally only partly loaded since it operates in parallel with other units fed with boiler steam and can take over the load in case of failure [10]. Five wells currently produce 369,000 lb/hr of steam. Heat exchangers are installed to produce clean steam for some of the processes [102].

Presently, there is no plan for the expansion of this plant in the near future.

Broadlands geothermal power plant is in initial development stage of planned capacity between 90 and 120 MW and proven possibly a further 50 MW. Since 1960, it is considered as a reasonable target where about 50 percent of the steam required already being available. Production is obtained between 450 and 750 m depth, but most wells have been drilled deeper to obtain geological data and temperatures at depth.

The maximum temperatures are 270°C or more, and the wellhead pressures in closed wells are high due to gas which has accumulated above the water. Original formation pressures are fully hydrostatic (about 75 kg/cm^2 at 460 m or about 920 m depth), and the wells produce steam and water. At a pressure of 7 kg/cm^2, the steam output is between 24 and 100 metric tons per hour, and the water output is between 27 and 160 tons per hour. The average capacity for eight wells are 58 tons of steam and 81 tons of water per hour. The average steam capacity for power production per well is estimated at about 2.8 MW [127].

The Broadlands geothermal power station is programmed to come into operation in 1976.

Besides the above mentioned geothermal power plants, there are several sites for which power plants are in the planning stage, with minor drilling activities, such as:

Ngawha, one well of 4 inches in diameter and 1,936 ft deep;

Orakeikorako, four wells of 8 inches in diameter and depth ranges between 3,800 and 4,600 ft ;

Reporoa, one well of 8 inches in diameter and a depth of 4,390 ft;

Rotokawa, two wells of 8 inches in diameter and a depth between 2,887 and 3,931 ft, and one well of 6 inches in diameter and a depth of 1,000 ft;

Tauhara, four wells of 8 inches in diameter and a depth ranging between 3,400 and 4,000 ft, and four wells of 4 inches in diameter and depth between 900 and 1,300 ft;

Te Kopia, two wells of 8 inches in diameter and a depth ranging between 4,085 and 8,080 ft;

Te Mihi, adjacent to Wairakei field, is an extention of that field and has been explored for possible future exploitation. Here, 26 wells were drilled during a period of seven years. Average depth ranges between 1,230 and 3,240 ft. Many of the wells give good production. One well within convenient reach of the Wairakei steam transmission lines has been connected to the system.

Waiotapu drilling was temporary abandoned, but drilling of a 7,500 ft exploration well is under consideration in the near future.

For the above mentioned sites, data are lacking for wells discharges, temperatures, and electric output capacity, except that the Tauhara site will have an estimated capacity of 15-20 MW, and possibly a further 20 MW [225].

In conclusion, there are no plans to construct additional geothermal power plants of large capacity in this decade. Industrial and municipal applications will be encouraged, and some generation of electricity may result incidentally to direct utilization of heat for industrial processes [10].

Other Applications

The large quantities of low-grade heat rejected as hot water from the separators of geothermal power stations using steam-water mixture have attracted much attention. This has resulted in the design of multipurpose installations using as much heat as possible from both the steam and water phases to achieve the greatest overall economy. It has been calculated that the hot water now wasted at Wairakei could provide central heating for a city of half a million people. Such multipurpose uses are few in number since in some geothermal fields (Wairakei) there are no prospective heat consumers located within easy reach of the power station [129].

Although the greatest amount of heat obtained is used for the production of hot water supply for central heating and for mineral baths by individual house-owners, there has been a considerable increase in the use of thermal water in hospitals, flats, motor camps, hotels, schools, commercial buildings and in industry. Besides the uses described, thermal heat is used in commercial glasshouses where out-of-season tomatoes are grown, as well as orchids and other types of flowers and exotic plants. The owners of these houses use heat from the thermal water to sterilize the soil. Other uses are for cooking purposes in open steaming ovens, where high temperature water is allowed to flash into steam. Private houses and smaller hotels use a simple type of open steamer. As well as cooking food for human consumption, waste food is steamed in low-pressure cookers and used as food on pig farms. The method has been found satisfactory and is approved by the health authorities.

Boiling water and cooking are done in urns equipped with stainless steel coils through which the thermal water is passed. Butchers use thermal water in cast iron and stainless steel pans for cooking and rendering of fats. It is also used for hosing down floors and cleaning and sterilizing vessels. Machinery workshops make use of thermal water for hosing down and cleaning greasy machine parts. It is used for ripening fruit and for heating steam boiler feed water, and flash steam from thermal water is used by boat builders for treating planking for yachts or launches. Flash steam is sometimes used in timber kilns, the kilns themselves being heated by thermal steam taken through gilled piping. Where pure steam is required in timber treatment plants, thermal water is used for steam generation.

Because of the high temperatures and the presence of impurities, thermal water is seldom used as it comes from the earth but is passed through heat exchangers, by means of which the heat is extracted.

The following are some examples of geothermal energy utilization for domestic and industrial purposes:

Animal husbandry. - Thermal resources are used at Taupo, where the B. & B. Co. operates a pig farm. Two wells were drilled on the fram to depths of 130 and 180 feet. The wells discharge a mixture of steam and water at an average pressure of 25 psi. Separators to remove excess water are fixed at each wellhead. Steam is taken to an open steam cooker, which consists of a concrete box with vapour-tight doors. The proprietors of the farm collect garbage from hotels and restaurants. This is put into steel drums which are placed in the cooker for 60 minutes. The cooked refuse is fed to the pigs. The owners keep 100 breeding sows from which are bred 1,500 pigs, known as "baconers", each year. The breeding sows are dept in a farrowing house where the floors are warmed from the steam.

In the fattening house, the pigs are moved progressively through a series of pens until they are ready for market. The floors of the pens are kept at an even temperature of 85°F throughout the year.

Steam is used for hosing down the pens and the feeding troughs, so that the pigs live in healthy and well-controlled conditions. It is also used for washinf down and sterilizing the empty garbage cans before they are refilled [228].

Chemical by-products. - The possible recovery of chemical from thermal waters at Wairakei is under consideration. Presently, the thermal water issued by the wells transports a total of 105,000 tons/year of sodium chloride, 13,000 tons/years of potassium chloride, and 2,400 tons/year of lithium carbonate. The estimated value of this chemical is about 6 shillings per 1,000 gallons of water. The chemicals can be recovered by a combined electro-dialysis - evaporation procedure. However, the total cost of recovery amounts to 7 or 8 shillings per 1,000 gallons of water, and process in therefore considered uneconomical and as such is under further consideration [8].

Heating and hot water supply. - The hot springs and pools have no doubt been used since the first Maoris moved into the Rotorua area some hundred years ago. Their villages were built around the thermal pools which were used for domestic purposes.

Today many of the Maori homes at Ohinemutu are centrally heated from geothermal bores and steam boxes are used to supplement electric ranges for cooking.

Records indicate that the first European domestic use was made by inserting a coil of steel pipe in a hot pool and passing water under pressure, through it. This gave a continuous supply of hot water and this is a method still to be seen today [137].

The thermal water and steam supplied by the wells at Rotorua have a temperature considerably above 100° C. The water is relatively impure. This has led to the use of indirect heating by means of heat exchangers. The house systems are closed and operate at a temperature above 100° C [8].

The <u>Wairakei Hotel</u> is supplied from a well approximately 1, 350 ft deep having a discharge of 4, 000 lb/h of steam and 2, 000 lb/h of water at a wellhead pressure of 60 psi. The water is separated from the steam at the wellhead, using a cyclone type separator. The steam is passed through heat exchangers at the hotel and used for heating and hot water supply. The steam leaving the separator has a dryness no greater than 99. 5 percent, and a 4 inch diameter pipe is used between the separator and the hotel. An additional supply of steam, which can be used in emergency, is taken to the hotel from the 20 inch natural steam mains which supply the Wairakei power station.

<u>Rotorua General Hospital.</u> - When the new buildings at Roturua General Hospital were being designed, it was decided to use geothermal water for heating and hot water supply (Fig. 62). To obtain a supply of thermal water, a 6 inch well tube was sunk 400 feet. The well yields from 2, 000 - 3, 000 gph at 243° F and 8 psi.

Water from the well flows through two sets of heat exchangers, under its own pressure, and before it is discharged into sumps, it again passes through a sleeve, where it preheats cold feed water to the storage calorifiers.

Although the calculated peak load for the hot water supply was about 2, 000, 000 BTU per hour, the average load was estimated at 600, 000 BTU per hour; it was therefore decided.

when designing the job, to use two 1,000 gallon storage calorifiers under a static pressure of 20 psi.

The first set of exchangers operates a close system from which water is circulated day and night through copper coils in the 1,000 gal. storage calorifiers.

From these, the thermal water goes to condenser-type heat exchangers with large heating surfaces, which serve the central heating system. All the calorifiers are fitted with thermostatic mixing valves, which control the temperature of the water supply to the various zones, and with emergency heating coils for use with boiler steam.

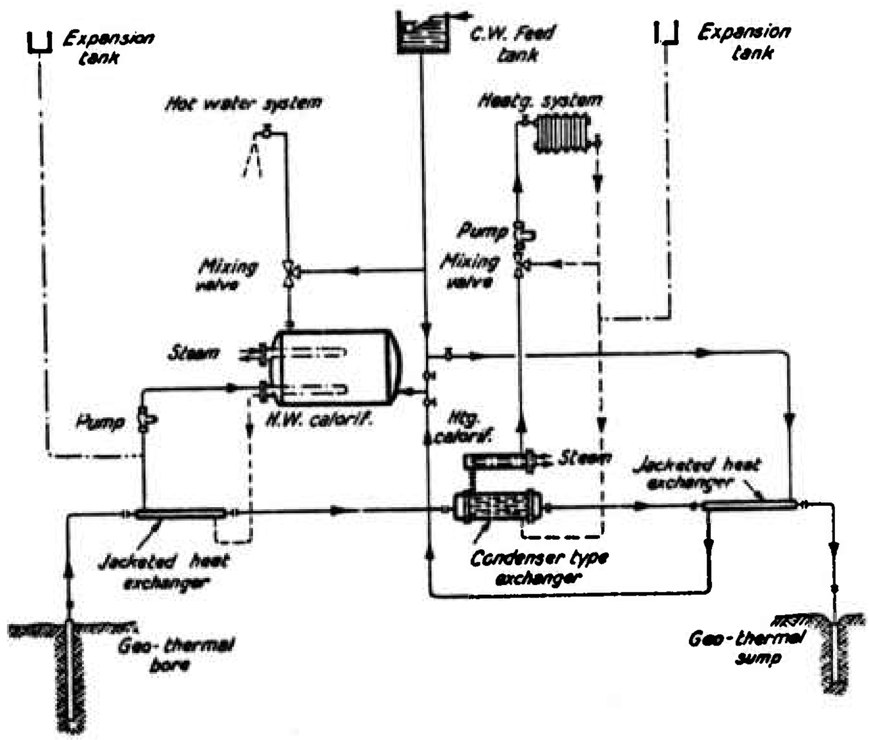

Fig. 62. Layout of geothermal heat supply of Rotorua hospital [228].

<u>The Forest Research Institute</u>, Whakarewarewa, is concerned with the growing, milling and treatment of trees and is an important factor in the economic life of New Zealand (Fig. 63).

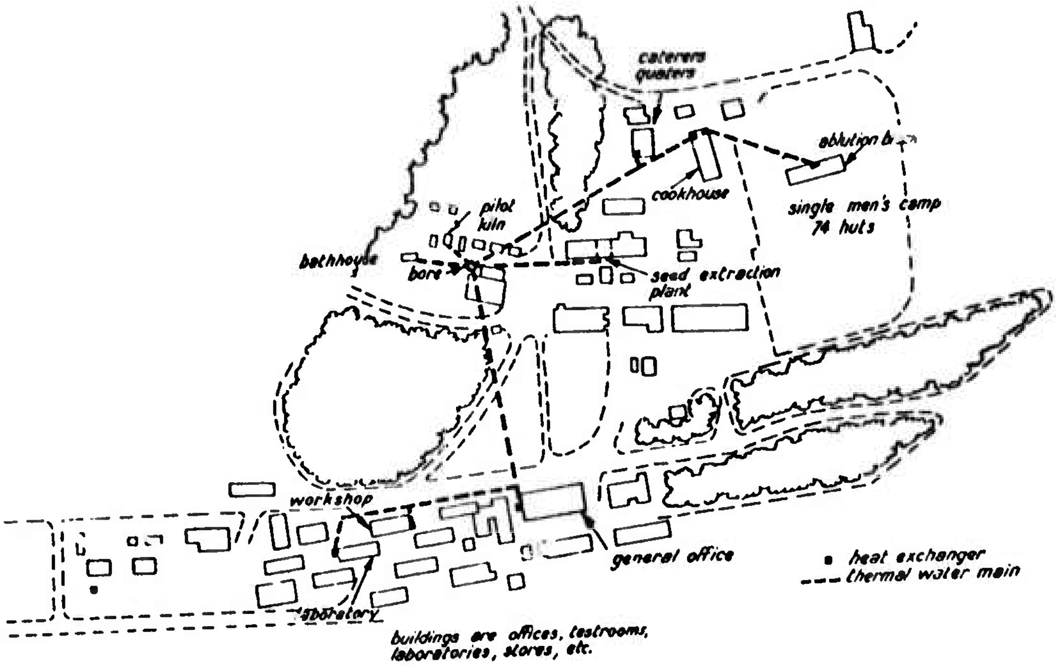

Fig. 63. Forest Research Institute, Whakarewarewa, New Zealand [228].

Besides laboratories and workshops, there are timber drying and timber testing sections, a seed extraction and nursery section, an office and administration section and hotels for the accommodation of staff and men sent to the Institute for training. The well supplying the Institute is approximately 650 feet deep and shows a pressure of 55 psi at the wellhead. The laboratories, glasshouses and groups of buildings are heated from standard type exchangers. Hot water is supplied from sleeve-type exchangers,

and cooking is carried on in a steam box supplied with flash steam. The experimental timber-drying kiln uses thermal water for drying pruposes and flash steam for the control of humidity. There are seed drying rooms where the thermal water is used to heat mild steel coils used for heating purposes. The control apparatus used in the seed drying rooms has not been found satisfactory for use with the thermal water, and it is proposed at a later date to use the thermal water to generate a supply of clean steam, which can be more easily controlled.

Rotorua Boys' High School. - As this school is not in the known thermal area, a well was sunk at a distance of approximately 4,000 feet from the school grounds, where there is a good supply of thermal water and from where there were no difficulties in taking the supply main to the shcool. The well was sunk to a depth of approximately 650 feet and can discharge 81,000 lb. per hour with a steam content of 13.7 percent and a wellhead pressure of 70 psi. The supply pipe to the school is run on conventional lines, with anchors and expansion loops where required. The pipe is wrapped with a tape and approximately 6 inches of fine pumice. Magnesium alloy anodes are fixed at each anchor point. The main has been in use for over 16 years. No trouble has been experienced either from internal deposits or from external corrosion on the protected section. The heat exchangers are designed on the two-pass system. The supply to these is controlled by thermostatic valves, which do not appear to be affected by the thermal water. After the water has passed through the heat exchangers, it is used in the school swimming pool (Fig. 64).

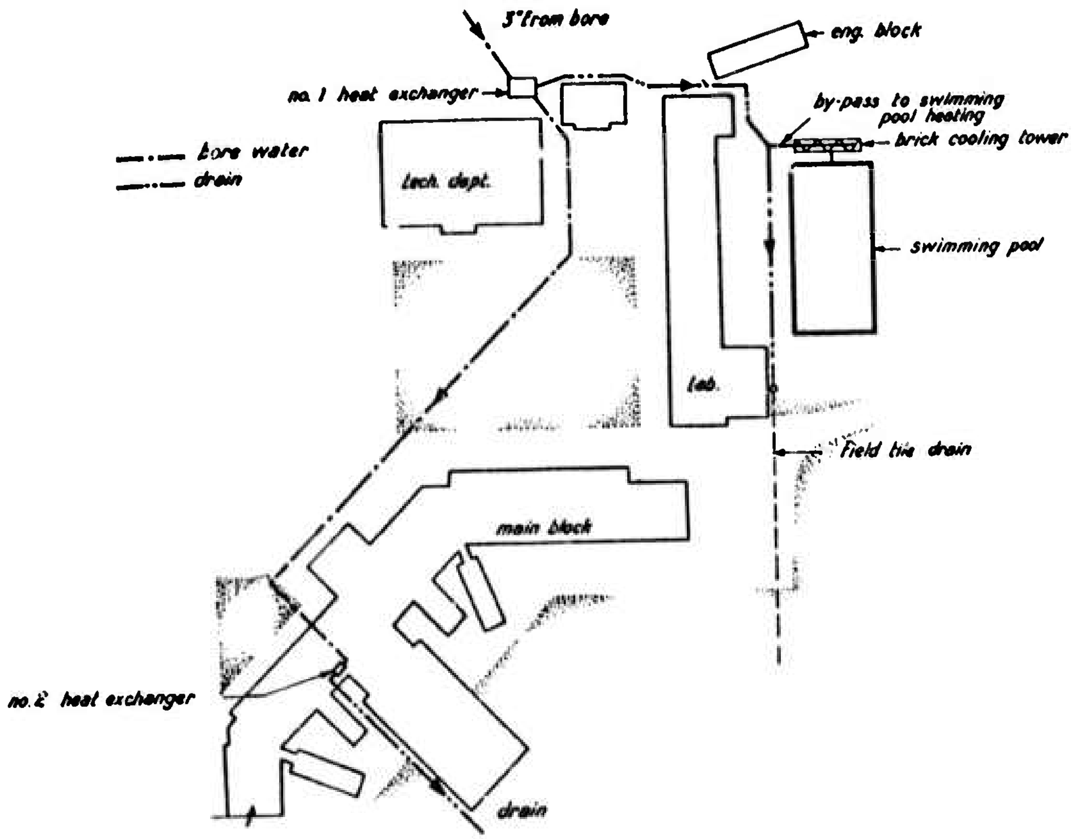

Fig. 64. The Rotorua High School, Rotorua, New Zealand [228].

In general, the development of geothermal resources in the area has been considerable, and it is expected that new industries will be attracted to Rotorus [228].

Besides heating and hot water supply, geothermal fluid is used as a means of cooking which is very prominent in New Zealand and outlined on pages 215 and 216 [134].

Refrigeration and air conditioning.- Fisher & Paykel Engineering contracted to design and build a geothermally-powered air conditioning and domestic hot water system for the new Tourist Hotel in Rotorua, New Zealand, involving about 2,000,000 BTU/h supplied by geothermal hot water. A buffer heat exchanger between the 300°F bore and 250°F clean hot water was used to serve absorption refrigeration as well as heating systems and domestic hot water calorifiers.

This project began in 1966 when Fisher & Paykel Engineering Ltd. were approached with a veiw to provide geothermally-heated plumbing and central heating services for a new hotel to be located near the Whakarewarewa thermal region in Rotorua, New Zealand, the original concept being for 100 rooms of hotel accommodation plus public areas of high standard as required for the tourist industry (Fig. 65).

However, it was clear that the expected temperature levels of the geothermal water were quite compatible with the use of absorption refrigeration for air conditioning. An investigation of the viability of this resulted in acceptance of the proposal for a contract on a design and build basis for full heating and air conditioning services plus hot water services all powered from a geothermal bore.

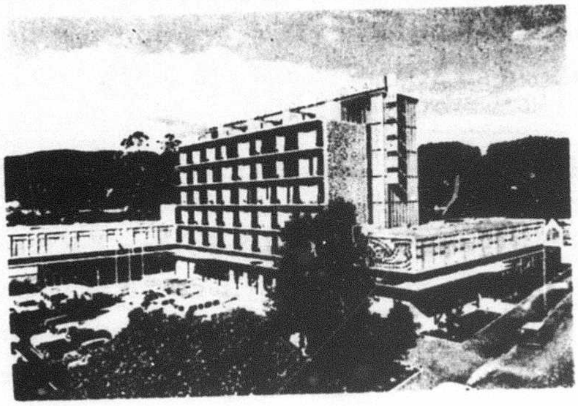

Fig. 65. Rotorua International Hotel, New Zealand [230].

Although New Zealand's island climate is temperate (Rotorua, approximately central in the North Island has temperature extremes of 25°F and 85°F), the consequent architectural licence means that heat losses are not necessarily as low as the temperatures would suggest. In this case the maximum total building heating requirement was 2,000,000 BTU's per hour and on top of this two fast recovery storage calorifiers were to be provided with a combined demand of 2,000,000 BTU's per hour for domestic hot water. The 130 ton lithium bromide absorption unit for the air conditioning required a heat input to the absorption unit of approximately 2.3 million BTU's per hours, usefully comparable to the winter heating load and thus levelling the heat demand on the bore between summer and winter.

The hotel has been opened for over six years, and apart from occasional bore shut down for minor service, it has been supplied continually with heating and cooling from the bore during that time.

The bore water itself is always available at temperatures between 300° and 340°F and pressures from 80 psig to 90 psig. The main fluctuation appears to be diurnal, and there is an absence of sudden surges.

The project itself was not a large one, but there seems to be no technical reason why the system could not be extended to many times the size, perhaps to a district heating and cooling system [230].

Medical and recreation. - Early in European development of Rotorua, spas were established. Many lake edge springs, varying from alkaline to acid, were developed and tourists and local people benefited from the use of these baths. With the growth of the tourist traffic, and the spread of reputation of the healing qualities of the waters, the Ward Baths, the Government Main Bath house, and eventually the Blue Baths were built. These all are becoming well known overseas for their therapeutic qualities.

The Rachael pool supplied the main baths for many years, supplemented by an acid water pumped through lead pipe from another surface pool some distance away. The Ward Baths were partially built over acid springs and alkaline waters piped from Whakarewarewa. This latter source also supplied the Blue Baths.

In Rotorua, originally developed as a tourist centre, many guest houses and hotels made use of the cheap and continuous form of heat, and most of them also advertised mineral pools as an added attraction.

The City (then Town) Council was also early in the utilization field by sinking a bore and heating Municipal Buildings and a theatre. Bores were sunk and utilized at the Queen Elizabeth Hospital, originally built in 1942 as a military hospital for American and New Zealand troops, and which developed after the war into the National Hospital for rheumatic diseases. A physiotherapy pool using cooled bore water was installed and a large section of the hospital changed over from boiler steam to geothermal heating. This led to the eventual complete change from boilers to full geothermal services. Steam generators were designed and installed to supply clean steam to sterilisers and cooking equipment in the up-to-date kitchen. Heat exchangers were designed and installed to supply the complete heating and domestic hot water services and finally a complete hydrotherapy unit, consisting of men's and women's "Rachael" baths (alkaline) and a "Priest" bath (acid); men's and womens "Aix" baths; and men's and women's mud baths were installed.

These units are supplied with mineral water from which heat has been extracted by heat exchangers and steam generators providing other services and run off into storage vats. The water is pumped under pressure to all points of use at 140°F [137].

7. Turkey

In 1961 the Turkish government began detailed studies of a series of geothermal manifestations in western Anatolia. The United Nations entered into a cooperative exploration venture in 1967, and the following year, after geological, geophysical, geochemical surveys, the first well was drilled at Kizildere, in the Menderes (Meander) river valley. Hot springs are widespread through this region, with temperatures to 100°C. Mercury mineralization is also present locally.

At least seven deep holes have been drilled at Kizildere, another at Tekke Hamman, 10 km to the southwest. In the process, a hotwater reservoir has been discovered, with two horizons, at depths of about 350 to 400 m and below 600 m. Exploration has revealed a highly fragmented horst and graben terrain, primarily with east-west trend, step-faulted down to the south. A crystalline basement of schist, gneiss, marble, and quartzite is overlaid by Miocene and Pliocene fluviatile and lacustrine sediments. A highly fractured Miocene limestone in this sequence constitutes the upper reservoir; fracture permeability in the crystalline rocks provides the lower reservoir. Quaternary alluvium caps the Tertiary sequence. No youthful volcanic rocks are present. Rather, the heat source is postulated to be a cooling granitic mass at depths of several kilometers. Its upward movement is believed to have generated the horst and graben structure.

Average well depth is about 450 m, and reservoir temperatures are between 180° and 200°. Yield per well is between 25,000 and 300,000 kg/hr, averaging about 150,000 kg/hr, with about 10 percent flashing to steam. It is reported that the deeper wells, into the crystalline basement, have higher flow rates. The reservoir fluid is highly carbonated, and a major problem of calcite deposition must be solved before development can proceed. The well at Tekke Hamman, in fact, is inoperable because of calcite inerustation. Reservoir fluid would be produced, utilized, and reinjected into the reservoir under pressure, thus avoiding the separation of salcium carbonate from the fluid [10].

In Saraykoy-Denizli geothermal area, the hydrogoe-chemcial study was used as an exploration tool and was carried out at the same time as the goelogical and geophysical surveys. The purposes of this study were:

- to provide information on the hot water system of the area, that is on its origin, evolution, and characteristics in the deep reservoir;

- to detect in the thermal waters possible information about evaporation-condensation processes, occurring in between the deep hot reservoir and the surface. These phenomena are possible when the hydrothermal reservoir is close to boiling conditions, so that " steam leakages " can occur through fractures and faults. Volatile substances accompanying the steam can concentrate in shallow aquifers, when the steam condensates into them. Among these volatiles, NH_4 and B are so far the most easily detectable and were the only ones considered in this work.

The analytical work was mainly carried out in the field, using portable laboratories. This procedure allowed an immediate availability of the analytical data, which permitted the work to go ahead better. Moreover, field determinations were considered necessary for some alterable components, like bicarbonate, calcium, ammonium, and silica. The analyses of these constituents were carried out directly at the spring site, together with the pH measurements.

Magnesium, sulfate, and chloride were analysed later in the camp laboratory. Selected samples were finally brought to the central laboratories (MTA, Ankara), where analyses were completed, with the determination of alkalis (not done in the field), boron, and fluorine.

The Denizli-Saraykoy area is part of an important graben approx. with an E-W trend, in which Mio-Pliocene lacustrine sediments are deposited on a Paleozoic metamorphic basement. Structurally, the basin is controlled by a regional WNW-ESE tectonic trend, which is responsible for the major sinking of the graben. Two other important systems, one NW-SE and the other orthogonal to it, are quite active on the western side of the area (Kizildere and Tekke Hamam). Here the basin is throttled by the uplifting, on the northern and southern flanks, of the metamorphic basement, and appears dissected into numerous fault blocks. This part of the area is the site of the most improtant themal activity.

Both surface and subsurface waters in the basin have shown a predominant Ca-Mg sulfate character. Their mineralization is obviously related to the gypsum bearing sediments of the Neogene series. Concentration in sulfate is variable, but can be very high (above 2500 ppm) in some cold springs and ground waters, particularly in the Tekke Hamam area. Another characteristic of the cold waters is the uniformly low content of Cl and Na, which generally are not in a stechiometric ratio.

More diluted, Ca bicarbonate waters, are instead typical of the cristalline areas surrounding the sedimentary basin. Intermediate, sulfate-bicarbonate terms, are the result of mixing between the two types. All these waters appear to be characterized by low concentrations of B and NH_4. B as an average, showed to be far below 1 ppm, NH_4, with some exceptions, below 0.2 ppm.

The hydrogeochemical data led to the conclusion that the hot water issuing in Kizildere represents essentially a direct liquid leakage of a deep hydrothermal system, circulating in the metamorphic basement, and chemically characterized by high concentrations of Na bicarbonate, boron, and fluorine. The other thermal waters of the Denizli-Saraykoy area appear as mixtures, at different ratios, between the same deep hot water (Kizildere) and local shallow cold waters, which are characterized by high concentrations of Ca and Mg sulfate, and by very low B and Na contents.

An estimation of the reservoir temperature can be based on the Na/K ratio. The Na/K ratio has proved in other geothermal fields, and in laboratory experiments, to be a regular function of temperature, provided the water is in equilibrium with the allumosilicates in the rock. Representing a direct flow from the deep aquifer, the Kizildere water could be reasonably considered in equilibrium with the reservoir rock. Its Na/K ratio indicates a temperature around 190°C.

The Denizli-Saraykoy area is characterized by a strong thermal anomaly, which is naturally evidenced by numerous thermal springs. The total hot water flow is 140 l/sec, at a temperature ranging from 35 to 100°C.

The area is not connected to recent volcanism, nor to visible young plutonic intursions. It is part of a very active tectonic province, in which water can probably circulate and be heated at a great depth. It is anyhow reasonable to believe that this deep tectonics could have mobilized subcrustal majmatic masses, which intruded the continental blocks up to an unknown depth. It must be rememebered that in numerous other areas of central and western Anatolia, geologically similar to the Denizli-Saraykoy area, intense volcanic activity took place during Late Tertiary and also Quaternary times.

An open problem is still whether the Kizildere water represents the actual deep hot water or is itself a product of mixture with cold shallow water. No well has so far tapped water directly form the metamorphic basement, so the problem is still unsolved. The Kizildere water indicates a temperature (according to the Na/K) of around 200°C. If it is still partly mixed with cold water, higher temperature could be expected from the original unmixed hot water [234].

At an early stage during the geothermal exploration programme of western Anatolia, it was felt necessary to attempt a division of western Anatolia into geothermal provinces.

Such a division into geothermal provinces based on geological, volcanological and structural criteria as well as on the character of the manifestations of hyperthermal activity, has greatly helped in rationalizing the general geothermal reconnaissance of western Anatolia and in determining the various prospective areas for further geothermal exploration.

Western Anatolia has tentatively been divided into 10 geothermal provinces of which the first six have been considered sufficiently promising to warrant a geothermal reconnaissance survey: Menderes massif, Izmir, Balikesir-Gediz, Manyas-Apolyont-Bursa, Afyon, Kizilcahamam-Bolu, Ankara-Haymana, Eskisehir, Beysehir-Konya, and Keyseri-Kozakli.

The Menderes massif geothermal province comprises essentially the Menderes crystalline massif and its associated graben depressions. The area of recent volcanic activity surrounding this cristalline massif to the northwest have been excluded from this province, more or less arbitrarily, because those area require a different exploratory approach.

Detailed geological fieldwork has been carried out in the framework of the UN. Geothermal Energy Survey of western Anatolia Project during the years 1967, 1968 and 1969 in all these prospective geothermal areas, whereas most of the fieldwork in the Saraykoy-Denizli and Turgutlu-Salihli areas had been carried out prior to the implementation of the Project by the Mineral Research and Exploration Institute of Turkey.

Deep drilling was only carried out on two locations in the Saraykoy-Denizli area: Kizildere and Tekke Hamam. Both are geothermal fields. Only Kizildere field appears at present to have the characteristics of a commercial discovery. Six wells were completed in the Kizildere field area between April 1968 and November 1969, whereas only one deep well was drilled on the Tekke Hamam location. Five additional wells have been drilled in the Kizildere field area since November 1969.

Geothermal manifestations - The Menderes massif geothermal province is characterized by two types of considerable heat flow: hot spring systems and recent mercury mineralizations.

The most important hot spring systems are apparently concentrated in those parts of the graben complexes where E-W and NW-SE, E-W and NE-SW or E-W and N-S fault zones are crossing each other:

Saraykoy-Denizli area
Turgutlu-Salihli area
Soke-Germencik area

The largest concentration of hot springs is in the Saraykoy-Denizli area where there are numerous springs ranging from 35°C in the Pamukkale spring system, to 100°C in the Kizildere and Tekke Hamam springs. The total discharge of these hot spring systems is in the order of 200 tons per hour.

The Turgutlu-Salihli hot spring system is not as important as the Saraykoy-Denizli area, possibly due to the fact that there is a less efficient cap rock over the main hot water acquifer and therefore more hot water can escape underground and become mixed with cold surface waters. The temperatures in the hot springs in the Turgutlu-Salihli area vary from 43°C to 82°C in the Turgutlu hot springs to 100°C at Kursunlu Hamam. The total discharge of these hot spring systems is in excess of 70 tons per hour.

The Soke-Germencik hot spring systems are less important than those in the Trugutlu-Salihli area. The temperatures of the hot springs range from 32°C in the Kemer Kaplicasi to 70°C in the Alangullu Kaplicasi. The total discharge of these hot springs is of the order of 40 tons per hours.

From the available information it would appear that the Menderes massif geothermal province is one of the most prospective ones in western Anatolia. The preliminary results in the Kizildere geothermal field are encouraging.

Although there appears that the entire central part of the Menderes massif province is characterized by an abnormally high heat flow, there are very few indications of this heat flow in the higher parts of the massif, where gneisses or cristalline schists are on the surface [232].

The Kizildere geothermal field was discovered in 1968 and is located in the Denizli and Aydin provinces of western Turkey. The field lies north of the Big Meander river between Cubukdag and Saraykoy, approximately 250 kilometers by road from the city of Izmir.

The field is situated in the northern part of a large hyperthermal area which occupies the eastern part of the Big Meander and Curuksu rivers.

The Kizildere geothermal field is for the time being a hot water field, from which steam can be obtained by flashing.

It appears that wells in this field, especially on the lower fault-blocks can make up to 32 tons of dry steam per hour and up to 400 tons of hot water at operating pressures between 5 and 6 ata. It has been established that the deeper fractured reservoir, in the crystalline basement, mainly composed of marbles, constitutes the main reservoir in this field, with a secondary, higher reservoir made up by the Mio-Pliocene limestones [223].

In 1975, in Kizildere geothermal area (300 km^2) about 130 testing wells have been drilled to a depth of 100 m, and 14 wells at a depth ranging between 500 and 700 m producing a steam-water mixture. Since 1970 preliminary work is under way for the construction of a geothermal power station with a capacity ranging between 25 and 50 MW. However, it is proposed to expand the generating capacity up to 200 MW, based on estimated potential of the area [231].

There is no doubt that the geothermal possibilities of Turkey are very large. Geothermal energy may be a major factor in providing power and heat to the country.

Turkey's economy is developing rapidly. The general conditions for a large exploitation of geothermal energy are present. Either steam or hot water may be used in power generation, space conditioning, industrial cooling, agriculture, many industries, and especially mining [127].

8. USA

Geothermal exploration in the United States has been of two types: incidental and directed. Incidental exploration has included geologic studies and drilling in thermal areas for purposes other than the development of geothermal resources. Incidental exploration has resulted in the drilling of countless hot water wells, and in the opening of many unusually warm mines and tunnels. Incidental exploration also led to the discovery of the Salton Sea, California, geothermal brine field in 1958.

Directed geothermal exploration began in the 1920s at several localities in the United States. At The Geysers, California, between 1921 and 1925, eight wells were drilled, by a private company, in areas of intense fumarolic activity. The deepest of these went to 640 feet, and dry steam adequate for the generation of perhaps 7000 kW was developed. Although technologically successful, the project failed for lack of adequate local demand for electric power.

In 1927 a group of private investors drilled three holes in an area of fumaroles and mud pots four miles north of the present Salton Sea field, in a search for geothermal steam. Steam was encountered, but in quantities inadequate for power generation. However, carbon dioxide gas was recognized in the discharge, and in 1932 drilling began again. The search for carbon dioxide was successful, and from 1934 to 1954, when rising waters of Salton Sea began to inundate the field, a commercial dry-ice plant was operated at the site. The deepest well, apparently,

was the original 1927 hole, to a depth of 1473 feet. The temperature of circulating fluid in that well reached 245°F. Ultimately over 65 carbon dioxide wells were drilled, about one half becoming production wells. The productive life span of a carbon dioxide well was about two years; total carbon dioxide production was in excess of 2.5 billion cubic feet.

The Geophysical Laboratory of the Carnegie Institution of Washington sponsored two shallow test holes into the Upper Geyser Basin and the Norris Basin at Yellowstone National Park, in 1929 and 1930. These research tests reached depths of 406 and 265 feet, and had respective maximum temperatures of 356° and 401° F. Steam was encountered in each hole, but after extensive geologic and thermodynamic studies the holes were cemented and sealed.

During that decade, also, extensive geologic studies were made at the geothermal areas of The Geysers, Mount Lassen, California, and Mount Katmai, Alaska.

In the early 1930s at Coso Hot Springs, California, several very shallow wells were drilled into fumarole areas in search for steam sufficient for electric power generation. None of the wells exceeded about 80 feet in depth, and the project was abandoned in the end.

Wells had been drilled at Steamboat Springs, Nevada, since about 1920 mostly to supply water to baths and swimming pools. Beginning in 1945 extensive data were obtained from wells drilled in this area.

As of October 1969, over 35 localities in the United States had been explored by drilling for geothermal fluids, more than 200 holes having been drilled in these localities.

Six producible geothermal fields have been discovered, although technologcial and legal problems have forestalled development at five of these fields. Only at The Geysers, California, is electric power being generated from geothermal steam. The others are Casa Diablo, Salton Sea, California; Beowawe, Brady's Hot Springs, Nevada; and Yellowstone National Park, Wyoming. Quite probably, Yellowstone National Park will never be developed commercially, but will remain in its natural state. At five of these six fields reservoir base temperatures are known to exceed 400°F; at Caso Diablo, although the shallow wells have not encountered temperatures above 360°F, base temperature is believed to approximate 400°F.

Several other geothermal prospects have been shown by drilling to have reservoir base temperatures of 350°F, or higher. These include Steamboat Springs, Nevada; Clear Lake, California; and Valles Caldera, New Mexico. None of these is considered to be a producible field at the moment. Base temperature is probably well above 300°F at Surprise Valley, California.

Over 90 percent of geothermal phenomena in the United States are in 13 western states, (Fig.66) comprising more than 1000 warm and hot spring and fumarole localities. Some 100 can be considered hyper-thermal. Expoloration in these areas has been of two types; incidental and directed. Incidental exploration has included geologic studies and drilling in thermal areas for purposes other than geothermal development. The Salton Sea, California, geothermal field was explored initially in this manner. Directed exploration has included geological, geophysical, and geochemical methods, and has resulted in geothermal test drilling in six states. At least six producible fields have been discovered: The Geysers, California: Salton Sea. California; Casa Diablo, California, Beowawe, Nevada; Brady's Hot springs, Nevada; and Yellowstone National Park. Wyoming. Reservoir base temperatures exceed 200°C probably at all of these fields. The Geysers produces dry steam; Salton Seal produces

brine; the others produce hot water. Only at The Geysers is electric power being generated; 83,000 kW of capacity has been installed, and facilities for an additional 110,000 kW are being constructed. At Salton Sea there is limited commercial production of calcium chloride from geothermal brine. Many insufficiently explored areas and marginal fields warrant additional directed exploration. These include; Surprise Valley, California; the Carson Sink, Nevada; the high Cascade Range in California, Oregon, and Washington; Valles Caldera, New Mexico; parts of the Aleutian Islands, Alaska; and the island of Hawaii. At least two geothermal prospects,

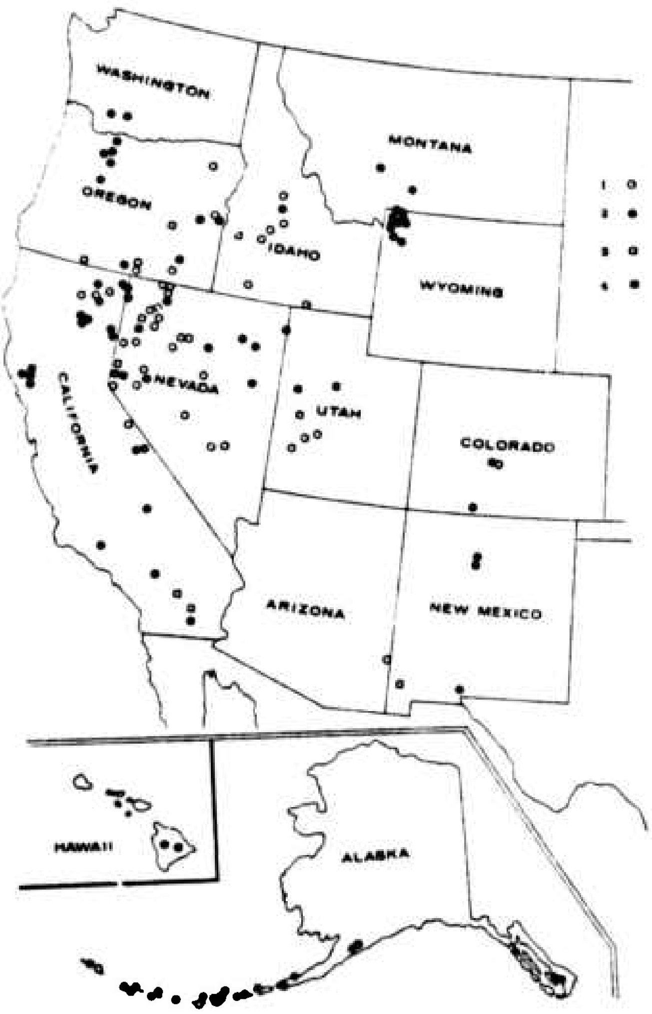

Fig. 66. High temperature phenomena in Western United States (T - 160° F) [240].

1- Single spring or fumarole; 2- multiple springs and fumaroles; 3- other basins of hot ground water; 4- mine shafts.

Clear Lake, California, and Steamboat Springs, Nevada, have been abandoned because of problems of waste water disposal and plugging of wells. These problems are encountered at other fields, including Salton Sea and Casa Diablo. Heat exchanging may provide a means to utilize these marginal fields. Several localities use geothermal water for space heating; outstanding of these is Klamath Falls, Oregon [240].

In the following are geologic characteristics, exploratory activities and chronologic data on developments of the known geothermal areas in the western states:

Arizona. - In 1973, drilling started on farm land, 2 miles southeast of Higley and 9 miles east of Chandler, Maricopa County. The steam producing well has a depth of 1,830 m, and it has been planned to contruct a geothermal power plant of undisclosed capacity [235].

California.

• The Geysers. - The first geological observations were made by Brewer in 1861.

After the exploratory activity of the 1920's the area remained idle until 1955, when extensive areas were leased by a private company, Magma Power Company, and drilling began anew. By 1957, six successful wells had been completed; on the basis of flow tests made at these wells, Pacific Gas and Electric Company signed a contract with Magma Power Company and its partner, Thermal Power Company, for the purchase of steam for power generation. At the time of completion of the first 12,500kW generating unit in 1960, a total of eleven wells had been drilled. One of these blew out during completion and remains uncontrolled.

The Geysers, of course, has been producing ever increasing amounts of electricity since 1960. Installed capacity is actually 83 MW. The power-equivalent of steam developed by drilling along a seven mile zone extending across parts of two counties, is more than 300 MW The location, spacing, and intensity of the wells suggest a total steam reserve in excess of 1,000,000 kW. Over 75 wells have been drilled, including those of the 1920s. More than 45 are now producible. The

Pacific Gas and Electric Company has indicated that it will add to its power generating system by annual increments of, perhaps, 110 MW. after the two units under contruction are completed in 1971. This implies that by 1975 on-line capacity may be 630 MW. Three companies or groups of companies, have drilled producible wells: the Union Oil Company - the Thermal Power Company - the Magma Power Company combination; the Signal Oil and Gas Company; and Geothermal Resources International. Many other companies hold permits or leases in the area.

The reservoir at The Geysers is composed of highly fractured graywackes, shales, and basalts of the Franciscan Formation, of Jurassic and Cretaceous age. Primary, lithologic permeability of the Franciscan Formation is extremely low. However, a large reservoir is implied by the spacial extent of sucessful drilling, by the rapid build up of pressure after a well is shut in, and by the high and relatively stable rates of steam flow. Recently completed wells have been to depths of 4000 to 8000 feet, and have averaged over 150,000 pounds of steam per hour. Permeability, therefore, probably exists in fault, shear and fracture zones, and perhaps along certain contacts, or in areas of high solution activity. Reservoir temperatures are in the order of 500°-550°F. Shut-in pressure of wells deeper than about 2000 feet is 450-480 psig. Superheat has been proved for several of the shallower wells, but cannot be demonstrated conclusively for the deeper wells. The apparent independence of shut-in pressure from well depth suggests that a steam phase exists for much of the field. However, the lack of widespread superheat in the deeper portions of the field implies that water and steam may co-exist, at least locally. The location of the steam-water interface, and the extent of water recharge is still a matter of debate. Shut-in pressures, especially for the older, shallower wells, have been declining, suggesting that the shallower portion of the field may not receive recharge adequate to maintain present rates of production. Many wells originally drilled to depths less than 1000 feet have been successfully deepened, with great increases of flow rate and shut-in pressure. This implies that the shallower, older portion of the field, which has its surface expression as

fumarolic activity along a prominent fault zone, may not communicate freely with the deeper reservoir.

Steam from the deeper wells carries a slightly greater content of gases than does steam from the more shallow wells. Approximately 50 ppm of boron are present. Condensate from the turbines cannot be discharged to creeks because of the boron. A disused steam well at the western margin of the field is now being tested as a disposal well for a portion of this condensate.

Heat source for the geothermal field is probably a buried igneous mass of Pleistocene age northeast of The Geysers, Cobb Mountain, a Pleistocene rhyo-dacitic plug, is the nearest youthful igneous body, being about 3 miles from the Geysers.

• Casa Diablo. - The first geothermal test at Casa Diablo was made in 1959. To date, approximately 11 wells have been drilled by the Magma Power Company and its associates. McNitt (1963) reported that the strongest of these wells tested 69,000 pounds of steam and 473,000 pounds of water, in 1960. This well reached only 630 feet in depth; the deepest reached only 1063 feet. All the actual wells are shut in, and none can be considered to be a production well.

Severe legal and technological problems have forestalled development at this field. Much potentially valuable land is unavailable for geothermal exploration at present; this has resulted in drilling being limited to only one of the hyperthermal areas of the Long Valley structural depression.

Thus it is not known how extensive a field may be present, or whether conditions encountered in drilling to date are truly representative of the reservoir or only marginal to it. Equally important, the residual fluid after steam flashover contains intolerable quantities of arsenic, boron and fluorine, and the operators may not dispose of this fluid into

surface waters or shallow ground water. Deposition of calcium carbonate in wells is also a problem. Direct reinjection of waste fluids in to the Casa Diablo field is contemplated.

The structural depression of Long Valley is approximately 20 miles by 10 miles in size, and is bordered on at least three sides by faults. Casa Diablo lies at its western margin, in an area of Pleistocene volcanic rocks. Composition of these is largely rhyolitic, latitic and andesitic; many are younger than 700,000 years, according to radiometric age-dates. Depth of volcanic and alluvial fill may exceed 8000 feet. There are very extensive fields of Late Tertiary and Quaternary volcanic rocks to the north and southeast. These also are marked by hot springs activity. Shallow wells drilled at Bridgeport and Fales Hot Springs, 50 miles to the northwest, were unsuccessful [240].

• Area of Calistoga.- Napa County, is located SSE of the Big Geysers zone.

Three wells have been drilled in what is called the Franciscan formation of Jurassic sandstones to over 100 m depth.

The area is covered by a thick layer of alluvium, making it difficult to determine the structural geology [14].

• Salton Sea. - In 1957, a wildcat test for oil was drilled about five miles to the south of the 1927 geothermal tests at Salton Sea, by the Kent Imperial Oil Company. The well, Sinclair No. 1, was drilled to over 4700 feet, and produced brine at a temperature of nearly 600°F. Thereafter, oil and gas possibilities of the region were forgotten, and several companies were organized expressly to explore for geothermal steam.

Until 1970, 12 wells have been drilled, in addition to the three wells drilled in 1927, and the several dozen carbon dioxide wells. One of these newer wells, drilled in 1965, is only 1700 feet deep, and was constructed to test disposal of residual geothermal brine by injection. The other eleven wells reach as deep as 8100 feet, and average about 5000 feet in depth.

The Salton Sea brine field produces fluid containing approximately 220,000 to 260,000 ppm total dissolved solids, mostly chlorides of sodium, calcium, and potassium, from a reservoir the temperatures of which reach 680°F at a depth of about 7000 feet. Data indicate that the brine pool underlies an area of 12 to 20 square miles, and that the volume of brine contained within the reservoir is in excess of one cubic mile. Structurally, the field lies alongside the southern extension of the San Andreas Fault, and within a major trough the origin of which is probably related to rifting apart from the westernmost corner of the continent. Some workers have suggested that the East Pacific Rise comes ashore beneath the continent in this region. The Cerro Prieto, Mexico, geothermal field lies within this same structural province, and it has been suggested that additional brine pools are associated with gravity anomalies located between Salton Sea and Cerro Prieto. These are being explored.

The reservoir at Salton Sea consists of highly permeable sands and silts of Pliocene age lying at depths greater than 3000 feet. These are capped by relatively impermeable clay and silt beds of Pleistocene and Holocene age. Positive Bouguer gravity anomalies within the Salton Trough are in part associated with five small obsidian domes of late Pleistocene age. More fundamentally, perhaps, these gravity anomalies represent the denser state resulting from in situ metamorphism of Pliocene sediments to the greenschist facies.

Upon release in wells, about 20 percent of the brine flashes to steam, leaving a residual bittern concentrated to 330,000 ppm. Plans have been proposed to generate electric power, to recover chemical salts for sale, and perhaps to condense pure water for agricultural and municipal use, the region being an extremely dry desert. One estimate is that 250 MW could be generated from the field as presently defined. The contained lithium and cesium of the brine probably exceed known world reserves. For a 250 MW plant, annual production of potassium chloride would exceed 4,000,000 t. However, problems abound: disposal of the bittern into surface and ground waters is prohibited; solar evaporation requires very extensive land holdings; market conditions for sale of large quantities of potash, lithia, table salt, and calcium chloride are not very favorable at present, and may not improve markedly for several years;

the extreme corrosivity and scaling characteristics of the brine require specially constructed pipes, valves, separators, and turbines; even special machinery is necessary for harvesting salts from evaporation ponds. Development continues on a very limited scale, the episodic production of calcium chloride solution for sale being the most notable result.

Field explorations in 1975 and 1976 in the Salton Sea area are intended to enable researchers to select a site for a ten megawatt demonstration power plant scheduled for operation by 1980.

• Surprise Valley, in northeastern California, is separated from the Warner Range, to the west, by a prominent fault scarp. A mud volcano erupted suddenly in 1951 in this area, at Lake City. In 1959 and again in 1962 this area was drilled by the Magma Power Company and its associates, a total of 4 holes being made. A maximum depth of over 2100 feet was reached, and the maximum temperature to be 320°F. (Another hot springs area was drilled 10 miles to the southeast, with less success). One hole nearly 2000 feet in depth penetrated only alluvial and lacustrine fill of the graben. Depth to basement is unknown. Intrusive rocks of probable Pliocene age form part of the summit of the Warner Rnage in this region. In the valley to the west of the Warner Range, an unsuccessful oil exploration hole encountered a temperature of nearly 300°F at the depth of 9564 feet [240].

Hawaii.- Kilauea-Iki volcano. The eruption of this volcano in 1959 formed a lava lake over 100 m deep in the crater, containing about 100 million metric tons of molten lava. The heat deposit is the lava stored in the crater.

Drilling and thermal surveys indicate an energy source from which about 2×10^9 kWh can be recovered [14].

The resulting lake of molten rock covered by a crust of solidefied lava offered a unique opportunity to attempt a drilling experiment

through rock at temperatures exceeding 1,000°C into molton lava. The crust-melt boundary was encountered at about 19 feet, and the melt was quite fluid at 20 feet.

This drilling was conducted as an experiment to learn the difficulties in drilling very hot rock. With improved selection of drilling equipment it is probable that air drilling would work satisfactorily to 1,000°C with standard drilling equipment.

It has been estimated that the Kilauea-Iki lava lake is a significant energy source, containing about 2×10^9 kilowatt - hours of recoverable power.

Completion of the experiment demonstrated that feasibility of drilling into hard rock formation at temperatures up to 850°C, using standard core-drilling equipment and compressed air to cool the drilling tools and remove the cuttings. Using a mixture of water and air as the coolant, it is possible to drill with standard equipment into rock at temperatures exceeding 1,050°C [244].

<u>Idaho.</u>- Thermal water has been known in Idaho since the beginning of permanent settlement in the middle 1800's. The most common uses of the State's thermal waters during the past century have been for recreation, irrigation, and space heating.

More than 30 recreational facilities located around naturally thermal waters are operating in Idaho. Most of these resorts specialize in recreation, not the health or curative aspects of the water, although most mention it incidentally.

The largest volumes of thermal water in Idaho are used directly to grow crops. Most of the tillable land of southern Idaho receives less than 15 inches of precipitation per year, and all large sources of water are important for irrigation. The trend toward sprinkler irrigation, which cools water more rapidly than does furrow irrigation, allows an increas-

ed use of the thermal water in several areas of southern Idaho. Increased well drilling for irrigation use has been an important factor in the increase of knowledge concerning Idaho's thermal water.

One relatively large space heating operation continues within Idaho. Houses along Warm Springs Avenue in Boise have been heated with 77°C well water since 1890. The system supplies hot water to more than 200 customers.

Sun Valley, the world famous resort in Blaine County, was developed, in part, because of the large number of thermal springs in central Idaho. Here, in addition to the recreational use of warm water, thermal wells and springs supply heat to many of the vacation homes along Warm Springs Creek.

Three greenhouses in Boise use thermal water for growing flowers; water has been used in such operations in the city for more than 50 years. A small greenhouse operation along the Middle Fork of the Payette River in Boise County uses thermal springs for growing flowers and vegetables.

Thermal water from Twin Springs which occurs 90 feet above river level, runs through a small Pelton wheel before discharging into the Boise river. This is the only thermal water in Idaho now used to generate electricity of undicslosed capacity.

In summary, most of the thermal anomalies in Idaho, and perhaps in adjoining areas in neighboring states, are ultimately related to residual heat of deepseated Cenozoic rock bodies that give rise to overall high heat flow rates and locally, to extra high thermal gradients.

The major mechanism for conveying thermal meteoric water and/or steam through the heating cycle is regional (and some intermediate) flow systems modified by major normal faults. Many of the faults have been conduits (aquifers) since Middle Tertiary time. It is impossible to

delineate further most of the flow systems and faults that are involved because the lack of detailed geological mapping in much of Idaho [239].

A newly discovered geothermal reservoir in southern Idaho may be large enough to be commercially important. A test well drilled by ERDA has produced a flow of about 1,000 gal per minute at 145°C from a depth of about 4,500 feet. It is reported that AEC/ERDA is investing $8 million for construction of an 10 MW pilot power plant over a geothermal hot water reservoir near Battle Mountain [236].

Montana. - In Marysville, Mont., a team headed by researchers from Battelle Memorial Institute in Richland, Wash., is sinking a well into what could be a multibillion-dollar geothermal hot spot. The thermal reservoir, covering a 10 sq. mile area, was apparently created by the intrusion of hot lava from the earth's mantle into its crust tens of thousands of years ago. Temperatures at the bottom of the well are 7000° to 8500°F. This first well is primarily a scouting probe designed to find out just how large and hot the deposit is. Exactly how the subterranean energy supply will be converted into electrical energy depends on whether it turns out to be an impermeable hot dry rock area as expected, or a hot water deposit. Drillers should determine this soon. Any prospects for commercial development are at least two years off. The three-year project is sponsored by a $2.5 million grant from the National Science Foundation.

It has been speculated that this reservoir is of magmatic origin, located at a depth of 1-2 km with estimated electric potential of about 200-1,000 MW for 25 years.

Nevada.

• Beowawe.- Approximately eleven wells have been drilled at Beowawe, by the Magma Power Company and associated companies, beginning in 1959. Several of these produced geothermal fluid, one well being capable of producing over 50,000 pounds per hour of steam, and 1,400,000 pounds of hot water, at a temperature of 342°F, and a well-

head pressure of 116 pounds. Production comes from less than 700 feet in depth. Infiltration of cool ground water into these shallow wells has lowered temperatures, and probably rendered them noncommercial. Therefore, despite the magnitude of flow from the discovery wells, no production wells have been completed. Temperatures as high as 418°F have been encountered in drilling, and these probably are representative of reservoir conditions. These temperatures are encountered at depths of 500 to 700 feet beneath the sinter terraces through which steam seeps issue. These probably are controlled by faults forming a graben along the range front. On the floor of the valley immediately to the west of the terraces are hot springs, at least one of which sustains geysering activity. During drilling at Beowawe in 1959, as at Brady's Hot Springs, a fumarole was activated 30 feet away from the hole in progress.

The two deepest holes at Beowawe are to 1918 and 2052 feet respectively. These penetrated opalite sinter, sands, clays and apparently volcanic rocks; such materials are typical of basin fill in structural depressions of the Basin and Range province.

Although still not developed commercially, Beowawe represents a significant geothermal discovery.

• Brady's Hot Springs.-Nine geothermal test wells were drilled here, beginning in 1959. Seven, including the initial hole, were drilled by the Magma Power Company and its associates; two holes were drilled by Earth Energy Inc., now a part of the Union Oil Company. Several of these holes were extremely shallow. At least two have been deepened subsequently. One deep test reached 5000 feet.

Production of steam and hot water has been achieved from a shallow zone along a major fault. However, other zones of hot fluids have been encountered to depths of 5000 feet. As the result of drilling in 1959, fumaroles burst into activity along a three mile stretch of the mail fault.

Reservoir base temperature is probably above 400°F, whereas

steam and water flow temperatures commonly exceed 300°F. There is a major problem of deposition of calcite in wells at this field, and it has been suggested that heat exchanging by means of some commercial heat-exchangers may be necessary to achieve power generation. The Magma Power Company has contracted to have a 10 MW butane heat-exchanging power plant built for test at this site in 1971-72.

Brady's Hot Springs is at the margin of a major structural basin in Nevada that includes the Carson and Humboldt Sinks. As shown in Fig. 66, very many high temperature phenomena exist in the area. A well drilled 30 miles to the southeast, near Stillwater, produced large volumes of very hot water.

Deeper wells at Brady's Hot Springs have penetrated alluvium, lake beds, volcaniclastic sediments, and volcanic flows, probably of Quaternary and Late Tertiary age. Depth to basement in this area is unknown.

• Steamboat Springs.- At Steamboat Springs, test drilling has reached depths of over 1800 feet. However, most holes have been to depths of only a few hundred feet. White (1968) lists 36 wells in the Steamboat Springs area, plus several dozen other warm to hot wells in the 10 mile zone extending from south of Steamboat Springs north to Reno. Within the central portion of the field at Steamboat Springs, temperatures increase very rapidly, approximating the boiling point curve, and reaching as high as 340°F at 350 feet depth. Below this depth temperatures essentially do not change. Reservoir temperature was estimated to be about 350°F.

There are extreme problems of incrustation of calcium carbonate within wells, carbon dioxide being carried upward in the vapor phase. If uncontrolled, the scaling will cause severe reduction in flow within days.

The extensive zone of thermal manifestations implies that there

is an intrusive body perhaps in the order of 50 to 350 square miles yielding heat to convective cells beneath the Reno-Steamboat Springs area [240].

New Mexico.- Fifty-seven areas in New Mexico discharge ground water at a temperature of 90°F or higher.

The data for 46 areas have been field-checked and show that thermal waters occur in the western half of the state, primarily in the Rio Grande and Gila-San Francisco drainage basins; and only 16 areas have been discovered by wells whereas 30 areas are marked by springs. The water issues from rocks ranging from Precambrian to Cenozoic age with the Cenozoic rocks predominating. The waters which are associated with igneous and sedimentary rocks in about equal proportions and occur primarily in areas of extensive volcanism and secondarily in fault zones. The discharge may be from fractures directly, from beneath a talus cover, or from alluvium, or from some combinations of these (one spring discharges from a tufa mound). The median pH is 7.7, the median maximum-temperature is about 105°F, the median discharge of springs is 30.5 gpm, and the average concentration of sodium is 167 ppm, of magnesium 6.9 ppm, of calcium 37.6, of lithium 0.30 ppm, and of potassium 10.0 ppm.

The major factors to be considered in evaluating a thermal anomaly in New Mexico are: temperature, volume of discharge, dispersion-diffusion effects by water chemistry, and geological setting.

Based on these criteria, the most promising prospects for natural steam in New Mexico are the Animas Valley in Hidalgo County, the Cliff-Gila-Riverside area in Grant County, the southern Rio Grande trough, and the Upper Jemez River basin.

The available radioactivity data indicates that the radioactivity of thermal waters is as randomly distributed in thermal waters as in nonthermal waters.

Geothermal gradiants generally are greater in the western part of the State than in the east.

Heat flow measurements rnage from a low of 1.1 HFU (heat flow unit) in southern New Mexico to 2.77 HFU in the southeast.

The thermal anomalies in New Mexico are ground water anomalies. Each is identified by ground water discharging at temperatures of 90°F or more. However, no thermal anomaly anywhere in the world, directly associated with active volcanoes, occurs in dry or unsaturated rock. Therefore, to prospect for natural steam, prospectors must work with anomalous heat in dynamic ground water systems, in areas where the crust is relatively thin and heat flow values are relatively high [243].

As experimental geothermal drilling program, since 1972, under way near Jemez Springs is aimed at determining the feasibility of a different type of thermal energy production.

A 4 1/2-in. hole has been drilled to 2,575 ft as the first step in the program. Testing is continuing on the well, and complete evaluation of the project may take several months.

Primary purpose of the experiment is to study the possibility of producing thermal energy from shallow, dry reservoirs by pumping cold water into them, circulating it over hot subsurface rocks, and returning superheated water to surface power plants.

The work is under the direction of the Los Alamos Scientific Laboratory, which is operated by the University of California for the AEC/ERDA.

After drilling the initial hole into hot rock, 2 7/8-in. tubing was run and the formation fractured with conventional oil well methods. Planned tests include electric logging and down-hole television pictures to pinpoint the area of fracture.

If these tests look promising, plans are to move the rig about a half mile to the top of a mesa and start another hole which will go to 4,500 feet. About 50 yards away, a second hole will be drilled, to be connected laterally with the first hole.

Then cold water will be pumped down the second hole and over the hot formation. The superheated water will flow to the surface where it would pass through a heat exchanger capable of removing 150 MW of thermal energy. Then the cooled water from the heat exchanger would be reintroduced into the formation.

Once a moderated temperature difference has been established between cold water entering the input hole and hot natural convection, pumping would be discontinued except when makeup water was needed to keep the system full.

The "cycling" technique now being studied at Jemez Springs could minimize many of problems. The area includes the remnant of a huge extinct volcano whose magma chamber extends several miles beyond the rim of the crater formed by the collapse or subsidence of the central part of the volcano [245].

In 1960, the Westates Petroleum Company drilled an oil test into the Valles Caldera of Sandoval County, New Mexico. It went to a depth of 3675 feet and produced steam and hot water. It has been tested repeatedly since then, but probably is not commercially producible. Three other wells were drilled in this area by the Dunigan Tool and Supply Co., in 1963 and 1964. A maximum depth of 5600 feet was reported by summers (1965). Temperatures encountered are believed to be well in excess of 400^{o}F. Large volumes of steam and water are said to be produced from several horizons, the shallowest being less than 1000 feet, and the deepest known being over 3600 feet. Production is thought to fall off rapidly during testing; data are sparse.

The Valles Caldera is believed to have formed approximately one million years ago, collapse being followed by eruption of rhyolite domes and pyroclastic debris. The geothermal wells were drilled at the western edge of this caldera. There is an extensive belt of hot springs in the area; many of these issue near the caldera rim 240 .

Oregon. - Lakeview area was prospected with a well 199 m deep in view of the existance of thermal manifestations with temperatures up to 82.2°C. This area is composed of Tertiary and Quaternary volcanic effusions with blockfaulting.

Crump Lake area was little explored, and a well of 512 m issued hot water with maximum temperature of 76.7°C [14].

Utah.- As reported in June 1975, the first successful geothermal test in Utah was accomplished with testing of a well about 15 miles northeast of Milford in the southeastern part of the state. The test well, drilled by Phillips Petroleum Co., on a federal lease, indicates potential for possible commercial production of wet steam. The test was completed to a depth of 2,728 ft. with initial flow of more than 200,000 lb/hour at a temperature of more than 205°C.

Wyoming.

• Yellowstone National Park.- Yellowstone probably is the largest and most intense geothermal district in the United States. This district can be divided into separate fields or zones, as the areas explored by drilling are in part discontinuous, and extend for a linear distance of almost 40 miles. The northernmost of these is Mammoth Hot Springs, an area of massive travertine terraces. About 15 miles to the south of Mammoth is the Norris Geyser Basin, containing about a dozen geysers and several hot to boiling pools. Some 15 miles southwest of Norris Basin is a major zone of fumaroles, geysers, boiling pools and hot springs extending for nearly 10 miles southward. This zone is subdivided into the Lower, Midway, and Upper Geyser Basins, plus the Lone Star Geyser by itself two miles to the south of Upper Geyser Basin. The famous Old Faithful Geyser is in the Upper Geyser Basin. In addition to these major

geothermal areas, the Yellowstone district, includes many other fumarole, geyser and hot springs areas; these include Heart Lake, Shoshone, and West Thumb Geyser Basins.

The U.S. Geological Survey, since 1967 has drilled 13 holes in six localities at Yellowstone; Mammoth, Norris, Lower, Midway, and Upper Geyser Basins, and Lone Star Geyser. (The two holes drilled in 1929 and 1930 by the Carnegie Institution were Norris and Upper Geyser Basin). The deepest hole (1,088 feet) yielded the highest temperature (in excess of 460°F). In many holes isothermal conditions had not been obtained at the completion of drilling. Therefore, reservoir base temperature is probably higher. It has been suggested that base temperatures of 500°F, or even 520°F, may be encountered at depths of about 1200 feet, in at least one of the areas studied. Only at Mammoth Hot Springs, of the areas drilled, is the reservoir temperature significantly below 300°F. Several high temperature localities in Yellowstone are still to be explored.

At least one well drilled in this exploratory program produced dry steam. Others produced large flows of very hot water, a portion of which flashed to steam. These results are in basic agreement with those of the 1929 Carnegie Institution exploration, but suggest for higher reservoir temperatures over a larger area than studied in 1929.

Geologic and geophysical exploration of the Yellowstone region has provided dtat on a series of calderas extending from eastern Idaho across northwestern Wyoming. At Yellowstone National Park, three major ash-flow tuffs have been mapped, of ages roughly from 500,000 to 1,500,000 years. Younger than these ash-flow tuffs are basalt flows, obsidian, glacial debris, and postglacial tuffaceous and diatomaceous sediments. This suggests that volcanism, perhaps accompanied by resurgency within the caldera, has lasted into Holocene time.

Despite the success of exploratory drilling for steam, it is highly unlikely that commercial development of geothermal power will be allowed within the National Park.

Extensive areas in the western United States possess potentially favorable targets. Some, like the Mount Lassen and Long Valley areas of California, have been explored in part. Others, including the Aleutian Island chain of Alaska, are virtually unexplored.

A considerable amount of geothermal steam resource exists in the Ozark and Appalachian regions. Most of these regions have almost no surface manifestations, but hot rocks and underground hot water/steam reservoirs can be found in many places. The Appalachian region holds great promise for the energy problem on the Eastern Seaboard. From Maine to Georgia the mountain ranges could supply pollution-free electric energy, hot water to heat and cool new and existing cities, and otherwise utilize the so-called waste heat.

Geothermal prospecting. - Geologic mapping, accompanied by gravimetry, and sometimes supplemented by geochemical surveys, temperature-gradient measurements, and aeromagnetic surveys, have been the most widely used exploration tools. Commonly, when two or more companies have explored adjacent or overlapping areas, duplication of effort has occurred. At The Geysers, for example, at least three aeromagnetic surveys were made, independently. Some exchange of data has occurred, as in petroleum exploration.

Well-logging procedures are those of the petroleum industry. The difficulty in obtaining temperatures and other down-hole data has not always been resolved satisfactorily, and commonly the temperatures reported have been those of the circulating medium. Wells drilled by cable-tool method are less likely to have been logged adequately, although the openness of the holes often has allowed more accurate temperature measurements.

Seismic noise studies have begun at The Geysers, at least in experimental form and are reported underway at Valles Caldera. Infrared imagery has been attempted also at The Geysers, Casa Diablo, and else-

where.

The very detailed U.S. Geological Survey studies of the Yellowstone geothermal district have included geologic mapping, gravimetry, aeromagnetics, extremely detailed geochemical and thermodynamic studies, infrared imagery and test drilling of 13 holes.

Electrical resistivity techniques, gravimetry, and heat flow measurements are being used by investigators from the University of California at Riverside, in the Salton Sea area 240 .

Generation of Electric Power.- The overall goal of the national effort in geothermal research and development, as viewed by the newly formed Energy Research and Development Administration (ERDA), is to assure that 20,000 to 30,000 MW of commercial electric power generating capacity are brought on line by 1985, and substantial increases are also made in the commerical utilization of geothermal energy for nonelectric purposes, such as commercial processing and space heating.

If this goal is achieved, it would allow the Nation to produce an amount of energy from domestic geothermal resources that would cost several billion dollars per year at present imported oil prices. The recent Project Independence Report is even more optimistic, estimating that, with accelerated geothermal development efforts, as much as 27,000 to 40,000 MW can be brought on line by 1985, and if these objectives are achieved geothermal generating capacity will continue to grow rapidly after 1985.

Current domestic geothermal power production in limited to The Geysers field, located in Sonoma County, California, about 80 miles north of San Francisco. The original plant went on line in 1960 and today about 396 MW are produced from the ten plants located in The Geysers field. Plans call for The Geysers power production to be increased to 1,018 MW by 1979, environmental legislation permitting, with an ultimate capacity which may approach 2,000 MW, one-tenth of ERDA's low ten year projection.

To assist in the realization of 20,000 to 30,000 MW of geothermal power by 1985, the Federal government is supporting geothermal research and development and will also support the fabrication and operation of geothermal pilot plant facilities to demonstrate the practicability of selected approaches in utilizing the various types of geothermal resources to produce power.

The intention is to disseminate the results of these efforts to the utility industry, the geothermal resource development industry, and the public at large. ERDA's FY-1976 budget request for this task is $22.8 million. However, in passing through the Energy Subcommittee of the House Science and Technology Committee, the request was increased by $33 million to a total of $55.8 million, subject to the approval of the House Appropriations Committee and, of course, to subsequent House, Senate, and Executive action.

The construction and the initial operation of 20,000 to 30,000 MW of geothermal electric power generating capacity may involve a total investment in excess of $10 billion by the utility and resource development industries. Federal support of research and development is intended to reduce the uncertainty and risk associated with such massive private investment.

A significant increase in exploration and development of geothermal energy resources and a growing public awareness of the great potential of geothermal energy combined to make last year a milestone for the fledgling geothermal industry. In 1974, the oil and gas shortage gave emphasis to the precarious domestic reserve situation for fossil fuels causing some large industrial users as well suppliers of power to become concerned over the future availability of such fuels and to turn in increasing numbers to geothermal exploration as a means of securing future energy supplies.

The rate of drilling geothermal test holes has been increasing markedly. Such drilling in 1973 was up 44 percent over the 1972 level and

the first eight months of 1974 are reported to show a 22 percent increase over the full year of 1973. Some of the more significant of the recent geothermal wildcats are: the AEC/ERDA experimental hole in Valles Caldera at Jemez, New Mexico; the Geothermal Kinetics Inc. wells at Chandler, Arizona, and near Brigham City, Utah; the Union Oil Company discovery in the Valles Caldera; and the ERDA discovery near Raft River in southern Idaho.

The AEC/ERDA experimental drill hole was completed to 9.650 feet on the edge of the Valles Caldera, a Pleistocene volcanic crater in the Jemez Mountains west of Los Alamos, New Mexico. The drill hole encountered temperatures of about 390°F in dry crystalline rock of low permeability. In preliminary fracturing tests at a depth of 6,750 feet, hydraulic pressure successfully produced vertically oriented lens-shaped fractures with complete containment of water. This success indicates good prospects for creating useful geothermal systems in hot dry rock areas that lack sufficient natural fluids and permeability. but whose occurrence is thought to be widespread in the western United States.

The Geothermal Kinetics wildcats in Arizona and Utah are the results of exploration in areas previously unrecognized as having geothermal potential. The commerical applicability of these deposits has not yet been determined.

The Union Oil Company wells, also in the Valles Caldera, New Mexico, have penetrated what could become the second commercial power geothermal field in the United States as it appears possible that a steam or steam-water powered generating plant of from 50 to 110 MW will be constructed on the site.

The drilling in southern Idaho encountered water temperatures of 290°F and a flow of about 1,000 gallons per minute from a 4,650 foot well on a site selected by the U.S. Geological Survey. The hole is being developed further to determine if water temperatures and flow rates can

be increased, as a 300°F temperature and a 5,000 to 10,000 gallon per minute flow were sought by ERDA for a demonstration plant to produce electricity. The drilling is being sponsored by the State of Idaho and the Raft River Electric Corporation as well as ERDA.

New production facilities may be sited in the Imperial Valley California, long an area of geothermal activity. Chevron Oil Company is reported as proceeding with development plans that could result in the installation of about a 50 MW binery power plant at Heber. Also in the Imperial Valley, the consortium of the San Diego Gas and Electric Company and the Magma Company has been investigating the possible generation of electricity by the binary magmamax method. A plant utilizing this process may be constructed at Niland.

As the result of a six months study, the TRW Systems group has urged ERDA to proceed with plans for research and development of an advanced 10 MW electricity generating plant using power derived from deep geothermal wells at East Mesa in the Imperial Valley. The area is considered by TRW to be uniquely suitable for such a facility with a huge reservoir of water averaging 350°F, hot enough to be commercially valuable, at about 4,200 to 6,200 feet beneath the desert. The East Mesa field could be long lasting as the geothermal water would be reinjected into the reservoir as part of the process.

A potentially significant reservoir of hot water almost 300 miles wide and extending along the Louisiana and Texas coast at depths of 7,000 to 10,000 feet is under investigation of the University of Texas through a series of grants from several Texas utilities and the AEC/ERDA. Preliminary estimates indicate that the zone may be able to supply one--third of Texas' electrical needs for as long as 50 years. The geopressured reservoir contains trapped water saturated with natural gas at above normal pressure at temperatures of 300 to 500°F. Present work consists of well logging and geologic studies. A demonstration project may be feasible in three to five years with some commercialization possible in perhaps eight to ten years [238].

Besides geothermal power plants in planning stages, mentioned above, in the following technical data is presented on The Geysers power plant, California.

The Geysers Power Plant

The first attempt to develop geothermal energy to generate electricity at The Geysers was made in the 1920's. Two small steam engine generators drawing steam from shallow wells were used to light The Geysers Resort. Some 30 years later, the first large scale development was undertaken. In 1955 and 1956, the Magma Power Company and the Thermal Power Company obtained leases around the natural steam vents near the resort and began a drilling program. In 1957, the Pacific Gas and Electric Company (PG & E) tested the six wells drilled and found that they could power a small turbine-generator unit economically if steam could be obtained for about 2.5 mill/kwh. The following year PG & E signed a contract with Magma and Thermal providing for the installation of an initial 11,000-kw unit to be followed by additional units if the project proved successful. Unit 1 went into operation 1960, and unit 2, rated 13 MW, began operation in 1963. Unit 3 and 4, each rated 27 MW, went into operation in 1967 and 1968, respectively.

In 1967, Union Oil of California, which had also acquired geothermal land holdings, joined Magma and Thermal in an expanded joint venture that now holds some 15,000 acres. By 1970, PG & E had signed a new contract with the joint venture providing for the increase of geothermal capacity at an orderly pace. Units 5 and 6 went into service in 1971, units 7 and 8 in 1972. About 100 MW a year will be installed for as long as the steam suppliers prove up additional steam reserves in what is currently the world's largest known dry steam geothermal reservoir.

It could be said that the prototype unit 1 was a research and development project. Although there was some information available on the experience of the Italian and New Zealand geothermal plants, it was felt that only by building and operating a geothermal unit could this

energy source be proved as a competitive power producer. During its design, extensive investigations were made on power plant material, the configuration of the power cycle, and the power plant equipment.

The initial investigations were concerned with establishing the adequacy of the steam source. At that time, the steam suppliers were required to demonstrate sufficient flow from existing wells to supply the first turbine-generator unit. The pressure flow characteristics of the steam wells vary, but in general the flowing wellhead pressures decrease with increased production rates. Shut-in pressure on the wells is 450-500 psi (gauge pressure); and the steam has a constant enthalpy of 1200-1205 Btu/lb.

To fully utilize the energy of the steam, it was felt necessary to employ condensing steam turbines exhausting below atomspheric pressure. Since this area has no source of condenser cooling water, cooling towers had to be incorporated into the cycle as a heat sink.

Many investigations were conducted on the composition of the geothermal steam from producing wells. It was found that the steam has a noncondensable fraction that varies from well to well but averages less than 1 percent by weight. For purposes of equipment design, the fraction is taken as 1 percent. The range of concentration of noncondensable gases is shown in table below.

Gas	Low	High	Design
Carbon dioxide	0.0884%	1.70%	0.79%
Hydrogen sulfide	0.0005	0.160	0.05
Methane	0.0036	0.132	0.05
Ammonia	0.0056	0.106	0.07
Nitrogen	0.0016	0.0638	0.03
Hydrogen	0.0018	0.0190	0.01
Ethane	0.0003	0.0019	—
TOTAL	0.120%	2.19%	1.00%

By comparison, the noncondensable gases in the steam in a conventional fossil-fuel steam power unit amount to less than 0.01 percent by weight, these in fact owing mainly to air leakage into the condenser. Because of its smaller cost and trouble-free operation, it was decided to use steam-jet gas-removal equipment rather than mechanical vacuum pumps. Two stage jet ejectors are used; these have been found to make efficient use of the motive steam, which is at turbine inlet pressure. The first stage compresses the gases from the exhaust pressure of 4 inches Hg absolute to about 5 psia. The second stage further compresses the gases to about 14.5 psia (1 psi above atmospheric pressure) for discharge out of a stack extending above the power building. The inter and after condensers required to condense the ejector steam are barometric type direct-contact condensers. The ejectors consume about 5 percent of the full load steam flow to a unit.

The flow diagram for unit 1 is shown in Fig. 67. Except for flow rates and minor differences in arrangement of equipment, it is typical of the first four units. Several steam wells are connected to a single generating unit. Their combined production characteristics closely match the required full load turbine-inlet flow and pressure requirements. Centrifugal separators installed in the steam lines from each well remove small rocks and dust entrained in the steam from the wellbores. The steam lines from several individual wells are manifolded into a main line leading to one unit. Should a turbine-generator unit trip out of service, pressure control or relief valves on the main steam line will limit the pressure to 150 psig by exhausting steam to atmosphere through mufflers

Increasingly larger units have been installed at The Geysers Power Plant. Experience gained in operating the earlier units has assured the reliability of the power source, justifying the installation of additional capacity in larger blocks. With the costs of power plant equipment, construction, operation, and steam increasing, the one way to reduce production costs is through the economy of larger installations.

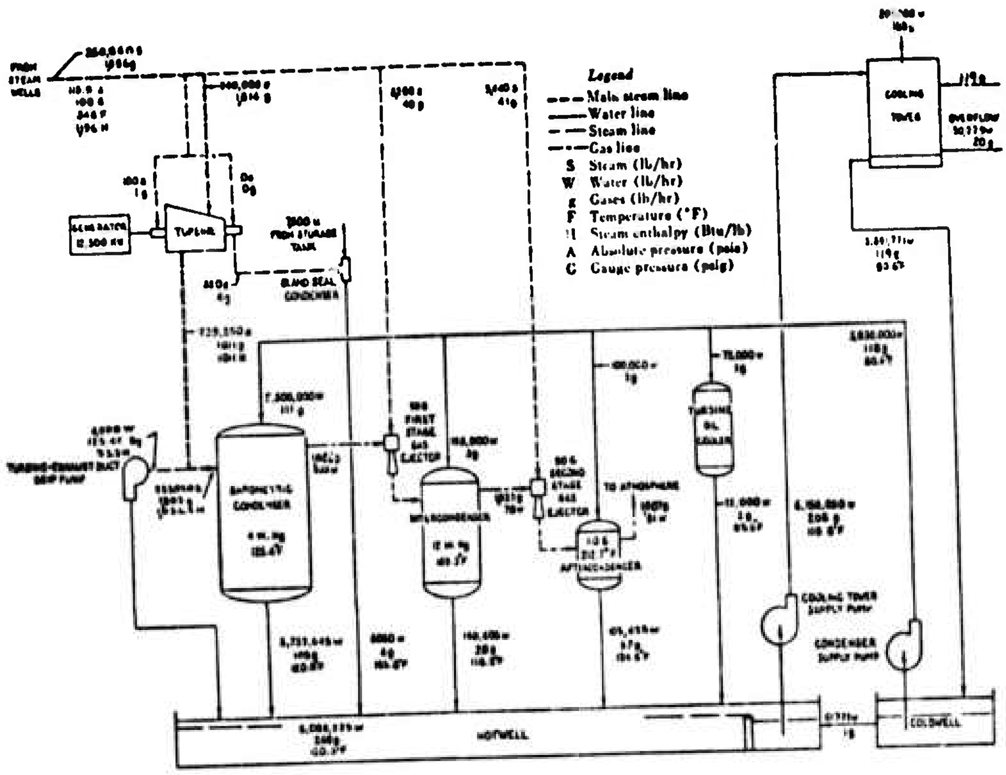

Fig. 67. Heat flow diagram for unit 1, The Geysers Power Plant [247].

In 1974, a single unit of 106 MW (unit 11) was placed in operation. Beyond this, no substantial increase in the size of the units is anticipated, owing mainly to transporation difficulties and the length of steam supply lines.

The cycle diagram for the 53 MW units (units 5 & 6) is shown in Fig. 68. The turbine steam conditions are 100 psig at 355°F (179°C) and 4 inches Hg absolute exhaust. The turbine is a single-shell, double flow design with 23-inch last-stage blades. Steam enters the turbine through two 24-inch lines, each of which has the same strainer and turbine-valve provisions as the earlier units. The design of the 106 MW unit (unit 11) has not been completed. The turbine, a two-shell, four-flow, 23-inch

last-stage blade machine, is essentially two of the 53 MW turbines in tandem. It is connected to a single large generator. The cycle conditions and plant arrangement will be similar to the 53 MW units. The distinquishing feature of these larger units is the use of the low-level-design direct contact condenser. Substantial plant cost savings result from the use of this type of condenser [247].

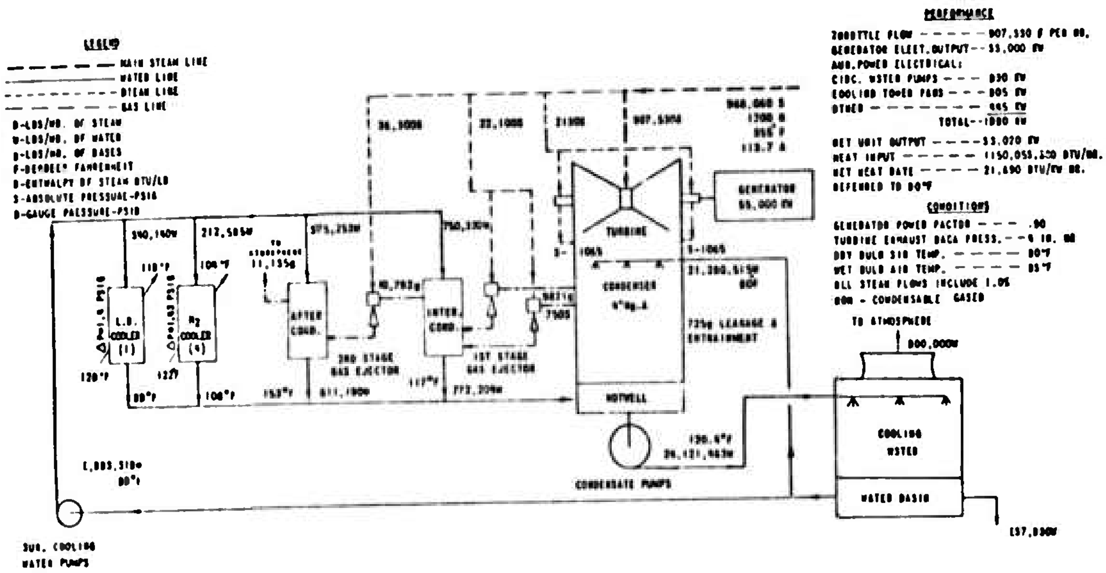

Fig. 68. Heat flow diagram for units 5 and 6, The Geysers Power Plant [247].

Steam is supplied from wells of varying depths. The early wells are from 200 ft to 1,000 ft deep and have flows from 40 lb per hr to 80,000 lb per hr. Recent wells vary from 2,000 ft to 7,000 ft in depth and typically produce 200,000 lb/hr. Steam at the inlet to the turbines ranges from 65 psig to 100 psig and has $8^{\circ}F$ to $10^{\circ}F$ of superheat.

Each 100 MW of capacity requires 12 to 14 wells to supply the 2,000,000 lb/hr of steam needed. For example, unit 5 having a net capability of 53 MW is delivered steam through a 36 inch OD, 3/8 in. wall carbon steel pipe connected to seven wells.

Units have been installed in pairs at different areas of the field. Fig. 69 is a map of the area showing their locations. The mountainous terrain of the area limits the size of major components transported to the site and the actual site area on the mountainside. Also, the pipeline distances of the steam collection system is a significant factor. A 100 M to 150 MW single site size appears to be the optimum [246].

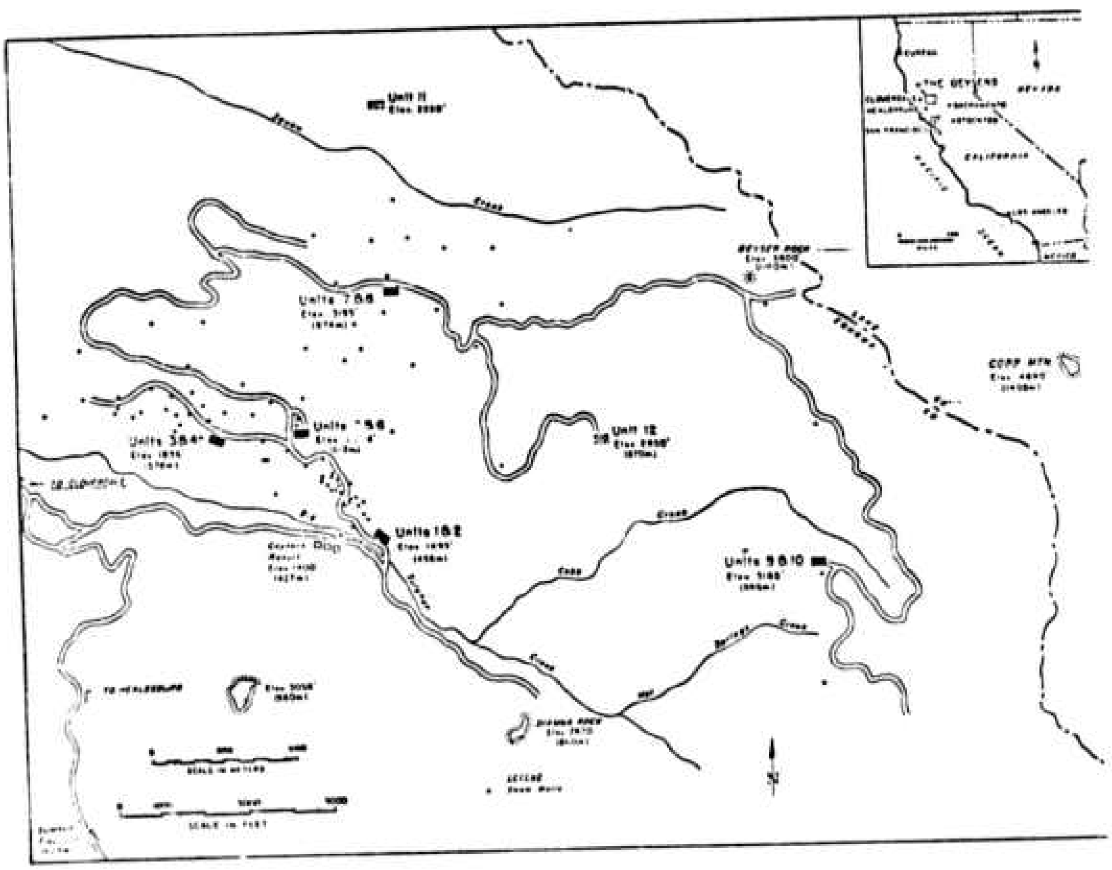

Fig. 69. Map of Geysers area with unit locations [246].

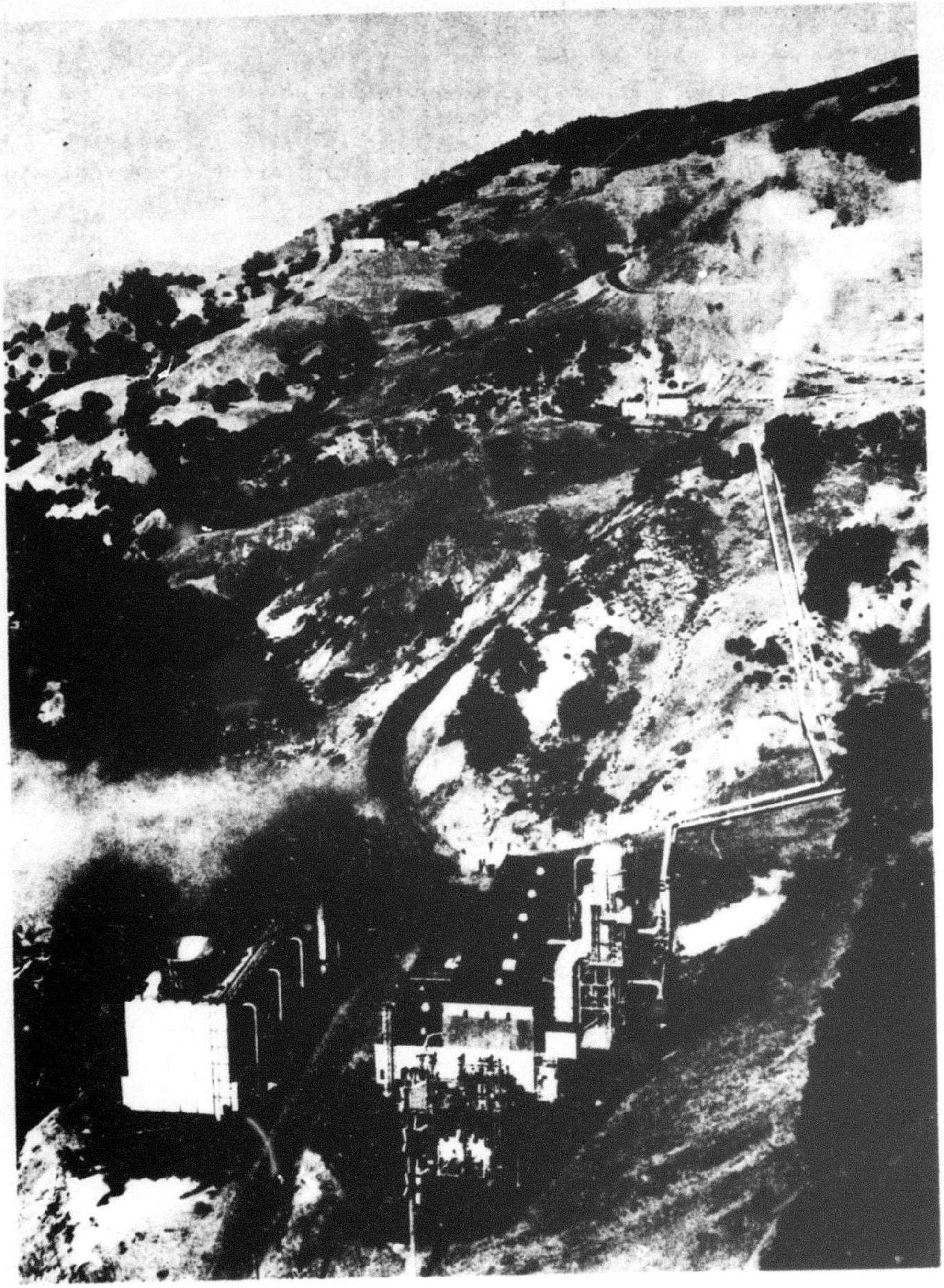

Fig. 70. The Geysers Power Plant (unit 1 and 2; units 3 and 4 may be seen in the background) [248].

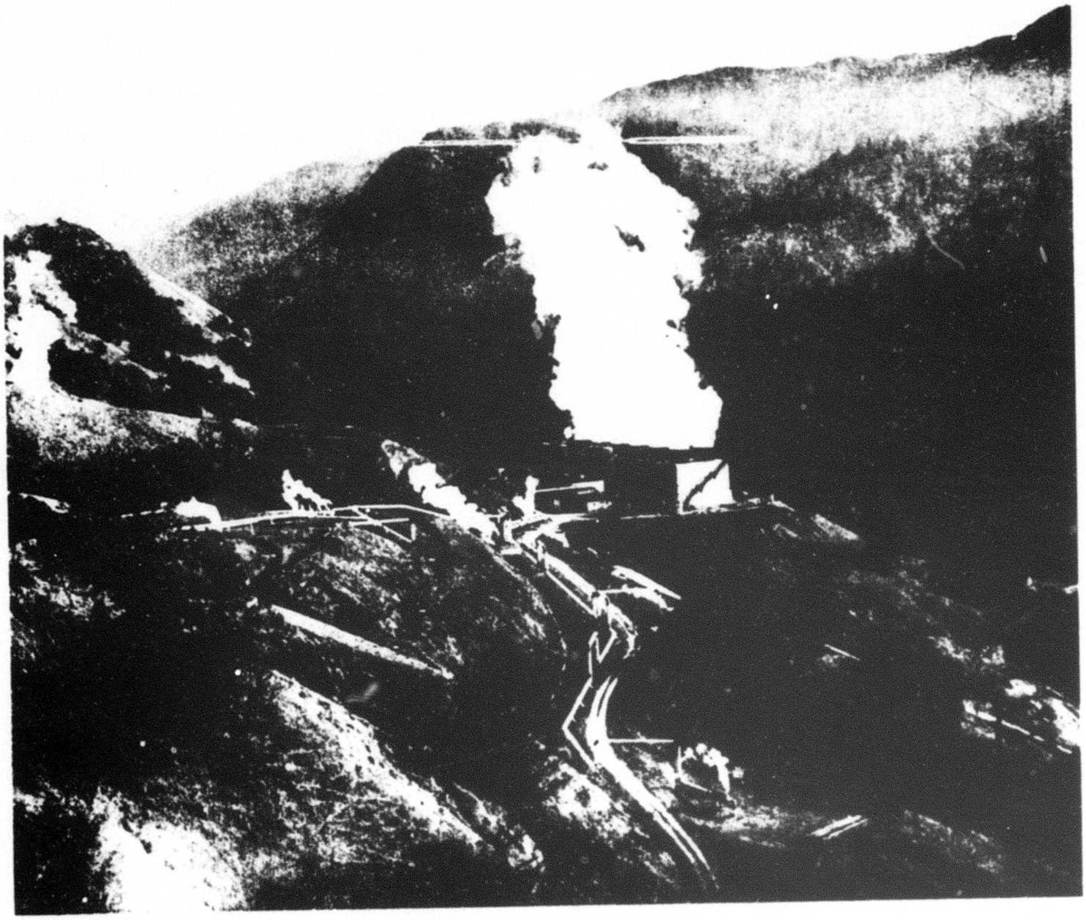

Fig. 71. The Geyser Power Plant (units 3 and 4) [248].

Based on the success of the early units, development of additional steam supplies and the construction of new generating facilities is moving forward at a rapid pace. The present rate of development is approximately 100 MW per year. Firm plans, contingent on adequate

steam supplies, called for placing units 9 and 10 in service in 1973, unit 11 in 1974, unit 12 in 1975, and another unit in 1976. The Geysers power plant will then have a net capacity of more than 700 MW. Additions beyond 1976 will be dependant on firming up additional steam supplies and determining if such power is economic to Pacific Gas and Electric Co. [246].

Several additional bores are being sunk every year and the boundaries of the field have not yet been reached. The field would appear to be the largest in the world. Steam equivalent to about 400 MW of power has already been proven, while the potential of the drilled area (which covers at least 20 sq. miles) has been conservatively estimated at 1,300 MW. There are reasons for believing that the exploitation of the whole thermal area could produce at least three or four million kilowatts [12].

Regarding future forecasting, the figures vary widely for total geothermal production, but estimates from 19,000 to 132,000 MW by the year 1985 have been given at various meetings by representatives of industry and the U.S. Geological Survey. By the year 2000, anywhere from 75,000 to 395,000 MW of geothermal power may be generated annually [117].

Other Applications

Besides generating electric power, geothermal energy has broad application in several branches of the national economy, such as:

Agriculture.- A large number of thermal localities have been used for domestic and agricultual water supply, or as water for livestock. In desert areas, condensate from fumaroles and steam seeps locally helps the growth of abundant grass for grazing. At Beowawe, Nevada, grazing for livestock is the sole use of the intense thermal field.

The Boise Cascad's Timber Group in 1974 constructed two new greenhouses adjacent to a hot springs near La Grande, Oregon. The natural hot water will be utilized to heat the greenhouses through the

winter months, providing a year-round growing climate for half a million seedling conifers a year. The controlled climate will produce growing stock two to three times faster than the conventional method where seedlings are raised in ground beds.

Boise Cascade will take advantage of the shortened growing period and low heating costs to mass produce trees to reforest large areas ravaged in recent years by the Douglas Fir tussock moth.

Chemical by-products. - The Salton Sea wells in California tapped brine at 340°C with very high salt content (220-260 g/l), and a pilot plant for obtaining valuable chemicals was in operation for many years. The geothermal waters in many fields provide great potential for extraction of K, Li, NaCl, $CaCl_2$, Mn, Su, Pb, Ag, and other elements [127].

Heating and hot water supply. - Hot water wells have been used for various purposes in the Klamath Falls area, Oregon, for decades. Many buildings in Klamath Falls have been heated by geothermal wells for years. The Oregon Institute of Technology, Klamath, having about 4 million square feet of floor space (eight buildings), is heated with the water from just one geothermal well. The hot water flows through heat exchangers in each of the buildings, heating air that is then blown into the rooms, as in any forced-air heating system. The Institute hopes to play a considerable role in the national geothermal program and is seeking governmental support to establish a National Center for Geothermal Technology. In addition, a hospital adjacent to the campus is also shifting over to geothermal heating [250].

Refrigeration and air conditioning. - Geothermal refrigeration has been under development for at least 10 years. In the United States today there is great emphasis on the production-line type refrigeration system with the result that absorption refrigeration systems are only available for the mass market created by air conditioning systems with geothermal water chilled to approximately 40°F (15°C) .

The basic cooling principle outline for use in the geothermal direct energy conversion system for cooling is capable of operating with considerable economy at minus $40^{o}F$ for all types of refrigeration duty. Increasing energy costs for the production of electrical power may soon have such drastic effects on operating costs for compression systems that geothermal low temperature developments may assume an important position.

Geothermal refrigeration systems represent one new step forward toward cooling without the usual conversion, from heat into electricity and then back into heat removal, which means instead a novel single step operation to save electrical energy [25].

Water supply (distillation or desalination). - The Bureau of Reclamation plans to use the Imperial Valley's geothermal brines as a source of fresh water to replenish the Colorado River decreasing volume and increasingly salty lower reaches. A 30,000 gallon per day pilot desalination plant is now operating near Holtville, California. It operates like the conventional desalting plants, except that it is not necessary to heat the brine which issues from the wellhead at $300^{o}F$ [236]. This plant has a total production capacity of 100,000 gallons per day. In initial high enthalpy of the Imperial Valley brine, there is sufficient energy left in the brine after 20 percent of it is flashed into steam (for power extraction) to permit its use for a desalination process. It was estimated that, in this case, about five to seven million acre-feet/year of low salinity water could be made available to relieve the above mentioned salinity problem of the Colorado River and to improve the irrigation of the Imperial Valley-Mexicali area. The technological and environmental problems of such a plan are substantial. It is possible that to deal effectively with high salinity brines closed loop cycles, such things as the Magmamax concept will have to be considered. However, any subsidence of the land could have a major detrimental effect on Valley agriculture because of the gravity irrigation from the Colorado River [84].

9. USSR

Historic Background Information. - Geothermal research in Russia started in the first half of the 18th century with several scientific expeditions engaged in measuring terrestrial temperatures in various mines in the Urals, Siberia, Altay, Volga region, and in the Far East. In 1906, scientist A. N. Ogil'vi developed a method for geothermal prospecting and exploitation of mineral waters. This method was applied also in prospecting for minerals, primarily oil and balneological waters. Information on terrestrial heat played an important role in the early evolution of geological science in Russia [252].

In 1910, the first Geothermal Commission of the Russian Geographic Society was organized and is credited with the collection of data on soil temperatures in permafrost zones and geothermal anomalies in the Caucasus.

After the revolution, geothermal research was given practical and scientific attention in national industrialization plans, though on a rather moderate scale and at a slow pace. In 1929, the first Geothermal Laboratory of the Central Scientific Research Institute for Geological Exploration was established to assume responsibility for geothermal research in the search for new natural resources. In the late 1930's, systematic thermometric observations were being conducted at several permafrost stations (operated by the Permafrost Institute of the USSR Academy of Sciences), with primary emphasis on the thermophysical constants of specific regions and large reservoirs.

Prior to World War II, intensive surveying and mapping of geothermal fields over a network of test wells was initiated, but was soon interrupted by the war.

In the early 1940's, by merging hydrological and geothermal doctrines, research was directed toward the development and exploitation of mineral and thermal springs. The most outstanding work of this period, Geothermal

Characteristics of the Caucasus, provided a new interpretation of the origin and distribution of therapeutic waters, terrestrial temperature, conditions for the formation and evolution of geothermy, depth of thermal flow, variations of heat gradients, and formation of ground waters [252, 253].

The All-Union Conference on Geothermy, held in Moscow in March 1956, stressed the great need for broader basic and applied research.

In 1963, the Plenum of the Central Committee of the Communist Party enacted a resolution, in a drive for overall expansion of the cehmical industry, to intensify research on and the utilization of geothermal resources, primarily on Kamchatka, and subsequently in the Caucasus, Siberia, and other regions of the Soviet Union. To coordinate these activities, the Earth Sciences Section of the USSR Academy of Sciences (established in 1961) was reorganized in January 1964 into the Scientific Council for Geothermal Research under the USSR Academy of Sciences [252]. This Council was strictly an administrative body, as all geothermal research was conducted and financed by various institutes, laboratories, universities, and several branches of the Academy of Sciences. Many valuable studies and collected works on geothermy and related subjects were published by the All-Union Scientific Research Institute for Geology and Engineering Geology, the Ministry of Geology, the Geological Institute, the USSR Academy of Sciences and its various branches, the Laboratory for Hydrogeological Problems imeni F. P. Savarensky, the Institute of Volcanology, and many others.

Presently, geothermal resources are considered as a new branch of the national economy. The Ministry of the Gas Industry has established several organizations and prospecting expeditions for broader development of geothermal resources in general, and multipurpose exploitation of hot water and steam in particular. In connection with these, considerable activity is underway in Dagestan, the Chechen-Ingush ASSR, the Georgian SSR, Kabardino-Balkar, northern Osetiya, Stavropol', Krasnodarskiy Kray,

Kazakhstan, and Kamchatka Oblast, while activities in the Caucasus and Kurile and Sakhalin Islands will be stepped up. To meet increasing demands for hot water, heating, and hothouse-greenhouse facilities, the Ministry's goal for the current Five-Year Plan (1971-1975) is to drill over 10,000 meters of additional geothermal test wells.

Since 1967, the utilization of geothermal water in the USSR has increased about 16 times. Several towns and industries have been supplied with hot water and heating, and the largest hothouse-greenhouse complex, completed at Paratunka in 1971, provides year- round fresh vegetables (previously imported from Vladivostok) to Petropavlovsk-Kamchatskiy and the surrounding area.

It has been estimated that the geothermal resources of the Soviet Union have a daily capacity of 22 million cubic meters of hot water* and 430,000 tons of steam. If fully utilized, this would save about 40 million tons of conventional fuel annually. The annual output set for 1976 is to produce about 15 million cubic meters of hot water and 470,000 tons of steam.

However, the development of geothermal resources is under the control of the Main Gas Production Administration of the Ministry of the Gas Industry, where a special Geothermy Department was established in 1963. The above Administration is primarily concerned with the extraction of natural gas, while geothermal resource development appears to be a secondary issue. The existence of this situation would not appear to be conducive to the fulfillment of the projected goals.

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* One of the world's largest reservoirs of hot water, extending over an area of about 3 million square kilometers, is situated in western Siberia.

There is evidence, corroborated by several Soviet geothermal research scientists, that the economic benefits to accrue from geothermal resources have been somewhat ignored and not revealed to the public as being comparatively cheaper than conventional resources, such as gasl, oil, coal, or peat. For example, on Kamchatka the geothermal heat is 6 to 15 times cheaper than heat produced by conventional thermal plants. Many geothermal experts are of the opinion that geothermal development cannot thrive as a separate discipline as long as it is subordinate to the gas industry. They further believe that now is the time for the establishment of a special organization which would be responsible for the promotion and development of this growing branch of the national economy [254].

Trends in Geothermal Research. - In spite of all the organizational changes and complexities of geothermal research, Soviet basic and applied research in geothermy has achieved considerable results for both the scientific world and the Soviet national economy. In general, this research is concerned with broad theoretical investigations, improvement of equipment and methods, and more intensive field exploration and prospecting [253].

In the last two decades, the hydrogeological deep drilling activities have contributed to the development of the new science of hydrogeothermy, which was applied to regional projects in the exploration and mapping of the geothermal characteristics of the USSR, ground water table, oil-bearing areas, and coal regions in the Donbas and other areas [252].

In 1967, the Aerial Surveying Laboratory of the USSR Ministry of Geology conducted the first exploratory survey on Kamchatka peninsula to determine the possibility of utilizing aerial infrared mapping techniques in studying volcanos and thermal anomalies. This survey concentrated primarily on the thermal characteristics of geysers and fumaroles, hot and warm springs, mud volcanos, mud pots, thermal streams and lakes, and other areas with thermal anomalies. The data obtained were correlated with field data and were used for mapping geothermal areas under consideration for development of their geothermal resources [56].

The Soviets have published a number of studies covering diverse subjects relating to various geothermal systems. Included among several subjects in these studies are: the measurement of the Moon's heat flow; the practical utilization of terrestrial heat; and the possible utilization of ground waters with low enthalpy, found in great quantities in the Soviet Union. Based on the regional synthesis of geothermal data, it is concluded that continental drift, which has separated the European platform from the Siberian platform, is manifested in the formation of a wide tectonic depression. The Soviets postulate that in the continental interior, the thermal energy released from the deepest part of the Earth (left uncovered by drift movements) is not dissipated by the cooling effect of oceans (which would come to occupy dislocated areas) and the energy thus maintains itself over a long period of time, creating regions with high geothermal anomalies [255].

Presently, the classifications of geothermal fields are based on chemical or thermodynamic criteria. There are proposals by several scientists that classification should be based also on geological criteria. However, some Soviet scientists differ with the present classification system of geothermal fields and suggest a dual classification of occurrence of thermal waters based on tectonic setting and type of heat source. Other proposals suggest the use of geological age, as well as tectonic environment [50]. The thermal gradients in the Ciscaucasus foredeep average about 30° C/km, and thermal waters ranging in temperature from 47 to 86° C are used extensively for balneological purposes, hothousing, and the dairy industry [28].

The occurrence of exploitable waters at a depth of 2 kilometers in the platform areas of the USSR, has been established in the West Siberian lowland (60 - 80° C) and in the Turana lowland, east of the Caspian Sea, (65 - 95°C) [255].

In early 1972, during intensive field research on geothermal gradients, heat flow, and coefficient of conductivity in the area of the Koryak-Avachin and Paratunka depressions, the Soviets obtained conclusive data that the volume

and distribution of anomalous heat flow rapidly attenuates near hydrothermal systems or magma chambers. This has been considered as a valuable indicator in propspecting for geothermal waters with the exploratory thermal corings [256].

Regarding geothermal system, on the basis of analyses of the content of U^{234} and U^{238} and other radioisotopes in waters of areas of active volcanism and neo-volcanic zones in the USSR, Soviet scientist postulate different circulation times for the water and the steam.

Vakin, E. E., et al, describing the situation at Kamchatka, observe that in regular observations conducted for many years, hydrothermal activity in conditions unaffected by exploitation undergo few or no changes with time. A different picture is observed under exploitation, there being a considerable decrease in the piezometric level and hence in hydrostatic pressure. Observation of the Pauzhetka deposit shows the discharge of boiling springs to fall in course of exploitation. The regime of the hot springs is thus closely linked to the deep system at high temperature. It is interesting that, during experimental exploitation of the Pauzhetka deposit, the sharp decrease in piezometric level was accompanied by transformation of a permanently functioning boiling spring into a geyser with reduced output. With its experimental exploitation terminated, and piezometric level restored, the former permanent discharge was resumed. This transformation involving hydrodynamic variations in the hyperthermal water system shows conclusively that geysers and boiling springs share the same nature, and also that geysers are a special type of boiling spring. A decrease in hydrostatic pressure in areas with low piezometric level gives more intensive steam separation and thus more surface steam discharge. This correlates with the fact that at the Pauzhetka deposit activization of surface thermal manifestations is not accompanied by temperature changes in the water-bearing complex. Consequently, the author concludes, within the same hydrothermal system one can observe signs of a weakening in hydrothermal activity (a decrease in discharge of the springs) and evidence of activization (more intensive steam separation).

The above described examples demonstrate that geothermal systems must be classified according to their character, and evaluated according to their potential, on the basis of characteristics which they can display after a certain period of utilization. It may also be observed that the manner in which this utilization is carried out can influence considerably the final result.

It is therefore extremely important to extend the knowledge which can permit prediction of modifications likely to affect a geothermal system following exploitation, and prediction of the times in which it is able to produce in different conditions. This above all for the purpose of programming the installations correctly [273].

Based on the chemical analysis and measured subsurface temperature from several drill holes, table below shows data summarized for several Soviet geothermal areas presently under exploitation or in the final planning stage.

Indicated and Observed Subsurface Temperatures in Explored USSR Geothermal Areas [39].

Area	SiO_2 content, ppm	Na/K ratio atomic	T_{SiO2}, °C	$T_{Na/K}$ °C	$T_{Max.}$ °C observed	Comments
Pauzhetka,						
Spring P. 1 (~100°C)	166	23.2	164	~156		VAKIN ET AL [27]
Well 4	302	16.0	194	193	195	
Uzon-Geyzernyy						
Geyser Velikan (~100°C)	294	16.9	200	187		VAKIN ET AL [27]
Bol'she-Bannaya						
Spring 4 (~100°C)	165	20.7	163	~167		VAKIN ET AL [27]
Well 35	223	22.0	177	~161	171	
Paratunka						
Spring (42.5°C)	62	63.1	111	~ 83		VAKIN ET AL [27]
Well 2	25	35.0	70(?)	~123	106	

The above data are fundamental for designing geothermal electric power plant of respective capacity and for selecting corrosion resistive material.

Abundant textual and graphical data on geothermy have contributed extensively to present Soviet geothermal engineering activities in the Crimea, Caucasus, Soviet Central Asia, western and eastern Siberia, and the Far East, including Kamchatka peninsula and the Kurile Islands.

Geothermal Development. - In the spring of 1941, the Soviet botanist Tatyana Ustinova made a major geographical discovery of powerful geysers in the southeastern part of the Kamchatka peninsula. Before that time, geysers were known only in Iceland, New Zealand, and the United States. Ustinova's discovery was to a certain extent a sensation, for in the middle of the 20th century, such a discovery is not frequent.

The first practical utilization of geothermal energy in Kamchatka started at the peninsula's southern tip near the large fish-processing plant at Ozernovskiy. Here, in the Pauzhetka river valley, between the Kambal'nyy and Koshelev volcanos, a vast territory of self-discharging hot water and steam vents (Fig. 72) became the site of the Soviet Union's first geothermal electric power station. Although, its capacity was not great. this project began a new chapter in Soviet power engineering and the development of the Soviet Far East [62].

In general, a long delay between the prospecting phase and the ultimate generation of electric power is common to all geothermal plants. In many cases, a delay of five years or more noticeably increases the capital cost of geothermal energy and it becomes a very serious obstacle to procuring the large amount of capital required for the exploration.

Fig. 72. Geysers in the Ozernaya River Valley (Kamchatka) [62].

The Paratunka power plant (USSR), the first freon*-operated plant in the world, offers convincing evidence that a power plant using natural hot water below the boiling point may offer a convenient solution. This type of geothermal power plant can be designed and built within the framework of existing engineering knowledge, technology, and construction capabilities; no revolutionary new design or new methods are required. A freon or isobutane hot-water plant may be designed and constructed without major innovations within existing production technology. In this regard, very large reservoirs of hot water above 80° C exist in many countries and can be easily harnessed by present technology [37].

Geothermal developments in the Soviet Union, for the most part, have followed an original pattern, differing significantly from the development patterns of other countries. In a recent study, it is estimated that 50 - 60% of the Soviet Union has deposits of thermal waters which are available for

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* Freon (trademark), any of a class of liquid fluorinated hydrocarbons used chiefly as a refrigerants such as the colorless and odorless gas dichloride-fluoromethane. Also used as propellants for aerosols.

economically effective use. The use potential of these deposits are comparable to the coal, oil, gas, and peat resources of the Soviet Union taken together. The thermal water reserves of the USSR at depths between 1000 and 3500 meters, with temperatures ranging between 50 and 130° C, have an estimated output of 7.9 million cubic meters daily. About 70% of these thermal waters are at depths between 1000 and 1500 meters [31].

Presently, there are eleven geothermal facilities in operation in the Soviet Union, with a total amount of consumed heat at 200 Gcal/hr, or about the equivalent of 125,000 tons of conventional fuel. An increase of at least 10 times this figure is forecast for the end of 1980 [257].

The basic factors governing the technical feasibility of utilizing geothermal waters are: temperature potential, discharge rate, depth of occurrence, pressure, chemical composition (mineralization, hardness, content of free carbon dioxide and hydrogen sulfide), and the amount of organic material and suspensions.

The economic expediency in utilizing geothermal waters depends on the geographic location of the source, accessibility and the condition of roads, the overall economic development of the region, and the availability of other types of energy resources. Based on hydrogeological and geothermal characteristics, the Soviet Union is subdivided into nine regions having different priorities and prospects for geothermal resources development [33].

To meet the technical-economic criteria, the engineering requirements for practical exploitation of a geothermal site in various regions and for different industrial applications are given in table below [33, 41].

It is estimated that there are over 150 areas and groups of individual springs with temperatures above 40° C. Some 19 of these have near-boiling temperatures, and about 40 have temperatures ranging between 60 and 90° C.

Type of utilization	Temperature, °C	Daily output, m^3	Depth of water-bearing horizon, m	Mineralization, g/l
Production of electric power by direct steam cycle	100	10,000	3,100	2 - 4(50)*
Production of electric power by intermediate low-boiling agent (freon, isobutane, etc.)	60 - 90	2,500	2,500	50
Heat supply for populated places	70 - 90	1,000	2,500	2(50)*
Refrigeration	70	500	1,500	50
Hot-water supply	40 - 60	1,000	1,500	1(50)*
Hothousing - greenhousing	40 - 70	500	1,500	10(50)*
Thermal irrigation	25 - 40	250	1,000	2
Heating of soil (for agriculture)**	25 - 50	500	1,500	50
Thawing of frozen soil***	25 - 50	250	3,000	50
Swimming pools & baths	25 - 40	250	1,000	50

* Figure in parentheses indicates permissible mineralization for geothermal plants with heat exchangers.

** During winter months or in permafrost regions.

*** Mining in winter months, in permafrost, or in the Arctic region.

The total discharge from springs having temperatures above 40° C is estimated as being over 140,000 cubic meters per second, with a heat equivalent of 10 billion kilo-calories daily. Recent research and prospecting activities in various Soviet republics foresee a complete inventory of geothermal resources as a contribution towards their more intensive utilization for heating, electric power, and other applications. The following are some of the major future developments planned for various republics and areas [45, 258].

Ukrainian SSR. Utilization of all thermal waters with various temperatures (70-80° C) and different degrees of mineralization for experimental-industrial installations.

Moldavian SSR. Pilot projects contemplate the use of thermal waters with different degrees of mineralization for agriculture, with new wells to be drilled near the towns of Kishinev, Ungen, and Bendery.

Crimea. Drilling is in progress at Dzhankoy, Feodosiya and Novoselovo, where surface manifestations of thermal water are present but where additional surveying is required to determine daily discharge, chemical composition, and temperature.

Georgian SSR. Thermal waters will be used in growing citrus, tea, and grapes, as well as for resort centers in the areas of Pitsunda, Zugdidn, Alazan, and others. At Tbilisi, it is proposed to obtain thermal water for experimental-industrial installations.

Northern Caucasus. Plans call for tapping thermal waters having various degrees of mineralization (10-50 g/l) and temperatures (60-100° C) for agriculture purposes, as well as for heating the towns Cherkassk, Armavir, and Nal'chik.

Azerbaydzhan SSR. Exploratory drilling is planned for Lenkoran and Masallinsk areas in hopes of providing thermal waters at temperatures ranging between 50 and 60° C for heating and hothousing complexes which will serve the European part of the Soviet Union. Presently, at Istisu, thermal water (54.5° C at the surface and 64° C at 50 m) is being used for balneological purposes.

Armenian SSR. Near the cities of Yerevan, Nalband, and Ankavana, prospecting work is scheduled to tap thermal waters with estimated temperatures ranging between 70 and 75° C.

Dagestan ASSR. Near the town of Makhachkala, drilling to a depth of 4500 meters is in progress to reach steam-water layers for a planned experimental-industrial geothermal electric station. Near the town of Berekey there is a highly mineralized hot water and steam well (Fig. 73) with a capacity of 70,000 cubic meters daily and a temperature at the surface of 57° C. It is estimated that this well can produce about $94.54 \cdot 10^{10}$ kcal of hot water annually, which is equivalent to 94,535 tons of fuel oil or 107,456 tons of coal [44].

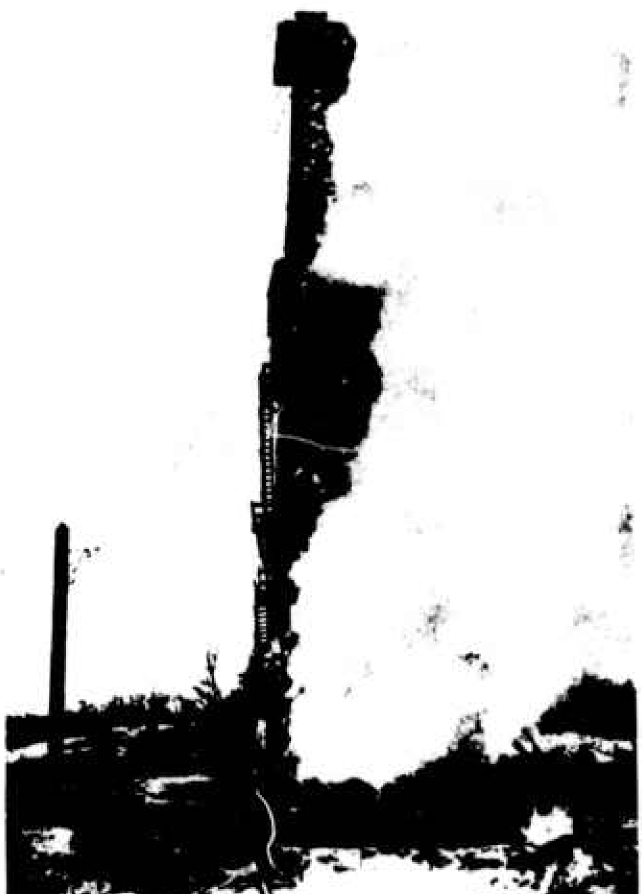

Fig. 73. Hot water and steam at well No. 3 near Berekey [44].

Kazakh SSR. Extensive prospecting is being conducted to determine regional thermal water characteristics (pressure, discharge, chemical composition, temperature, depth and capacity of water-bearing horizons), especially in the regions of Chimkent, Turkestan, Turgay, and northern Pavlodar Oblast, for ultimate agricultural applications in arid and semiarid regions.

Uzbek SSR. Extensive exploratory works are in the areas of Tashkent and Fergana.

Kirgiz SSR. Prospecting is planned for the Przheval'sk area to develop thermal water resources for space heating. In the Issyk'Kul' lake region, additional drillings will be conducted to determine balneological capabilities and in particular, space heating potential for several resort centers under construction.

Tadzhik SSR. Near the city of Dushanbe, several drill sites for thermal waters are planned, to provide heating and airconditioning to the city. At the resort centers of Khodzha-Obi-Garm, Obi-Garm, and Khabatag, the plans to increase output of thermal water and steam for balenological and heating purposes are in the final stage.

Western Siberia. To promote balneological resort centers, extensive drilling for thermal waters, ranging in temperature between 50 and 90° C with mineralization between 10 to 30 g/l, is in the planning stage.

Chukchi Peninsula. Exploratory drillings on Chukchi peninsula and in the coastal permafrost region bordening the Sea of Okhotsk will assist in studying the technical-economic indices of thermal waters for space heating, vegetable farming, and resort centers. Near the towns of Talaya and Motykleysk (about 125 km west of Magadan) exploratory drilling is in the preparatory stage, with the ultimate goal of obtaining fresh and low-salinity thermal waters for resort centers.

Under primary consideration for the production of electric power are the areas of Yevpatoriya, Nal'chik, Tbilisi, Tobol'sk, Tashkent, Bol'she-Bannaya, Pauzhetka and Sredne-Paratunka on the Kamchatka peninsula, Goryachiy Plyazh on Kunashir Island, Paramushir Island, and Chapiino on the Chukchi peninsula [258].*

In 1964, it was proposed that all exploratory and producing wells be reevaluated regarding their equipment status, water table, and water parameters. Areas under primary consideration are: western Siberia, the Tersko-Kumsk area, the Azov-Kuban' artesian basin, the steppe area of Crimea, the Ciscarpathian depression, the Dneprovsk-Donets basin, the Pechora artesian basin, the Kura depression and the adjacent region of the Apsheron peninsula, the artesian basins of the Georgian and Armenian SSR's, the North Caspian depression, northern Ustyurt, southern Mangyshlak trough, and the Sakhalin and Yakutsk artesian basins.

It is assumed that these evaluations will contribute to increasing the output of existing geothermal wells, reduce expenses for new exploratory projects, and assist in the discovery of potential deep terrestrial heat-flow sites. In addition, this survey of existing geothermal wells would serve to update regional and national geothermal resource data.

To achieve the above goals, it has been proposed by several Soviet scientists, geologists, and geothermy specialists, that the following steps be taken:

- To compile a map at 1:2,500,000 scale which would represent the quantitative characteristics of the exploitable thermal water reserves in the USSR. This map should be compiled by the Geological Institute of the USSR Academy of Sciences and the All-Union Scientific Research Institute of Hydrogeology and Engineering Geology.

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* Additional data on geothermal sources in the above republics and regions and their chemical compositions, temperatures, discharges, mineralization, gaseous components, and development potential for various areas of the national economy, are outlined in "Recent Soviet Investigations in Geothermy", Report 1, May 1972.

• To request that the Geological Institute develop a theoretical basis for the formulation of thermal waters.

• To develop procedures for the research and exploitation of goethermal waters, and to develop well technology and methods for the complete testing of thermal waters encountered while drilling for oil and gas. These activ ties should be conducted by the Balneological Institute of the Moscow State University and the All-Union Scientific Research Institute of Hydrogeology and Engineering Geology.

• To request full participation from the State Commission on the Natural Resources of the USSR, in defining basic conditions and requirements for thermal waters.

• To request the All-Union Scientific Research Institute of Hydro-geology and Engineering Geology to develop and provide basic economic estimates as guidelines for effective exploitation of thermal waters with varying temperatures and ratios of mineralization, and for various geographic areas [258].

Geothermal Electric Power Generation. - The enormous USSR reserves of geothermal waters having temperatures between 30 and 180° C could be utilized for purposes vital to the national economy, other than the generating of electric power [259]. The most efficient way is to use a low boiling heat carrier as a second working fluid. In this line, the experimental freon turbine power station represents a revolutionary innovation and appears to hold great promise for future Soviet geothermal power development and engineering [256].

The following are some highlights of Soviet engineering efforts toward solving some problems in geothermal power generation.

The Soviets have conducted extensive studies on the corrosion effects of geothermal waters on metals and alloys having various degrees of corrosion resistance, such as steel, chrome-nickel steel, gray iron, galvanized steel, copper, and brass. It has been established that for geothermal water containing soluble hydrogen sulfide or carbon dioxide, at a temperature of 70° C, the corrosion rate of low-carbon steel increases by about 25 to 30 times; with the water aerated and at a temperature of about 55° C, corrosion increases only by 10 times. To capitalize on this, the geothermal water is not used directly from the well, but is collected in an open reservoir for aeration, and is then fed into the heating system [260].

The Electric Welding Institute imeni Ye. O. Paton of the Ukrainian Academy of Sciences has developed several types of cavitation and heat-resistant austenitic steels, characterized by high weldability and stability through work hardening [261].

Soviets use low-level turbines with external barometric condensers, while other countries use high-level turbines placed above the condensers.

The extraction of noncondensable gases from the condenser is achieved by water ejectors, while some countries use steam ejectors, rotary exhausts, and reciprocating pumps.

Regarding the steam-control method, the steam is maintained at a constant pressure by blowing off variable quantities to waste, instead of allowing the steam to float to some extent by throttling at the turbine and thus reduce possible blow-offs [61]. The turbine's stop valve pressures, at the first point of feed from the field (i. e. excluding turbines fed from the exhaust from other turbines or flash steam), are generally very low [262].

As the first phase in the utilization of geothermal resources, the Soviets are presently concerned with the construction of small capacity geothermal electric power stations and heat-supply systems [51].

An advanced idea, originated by the Institute of Thermal Power Engineering of the Ukrainian Academy of Sciences and supported by the Design Institute of the Thermal Electric Station Planning Enterprise, to design a very large geothermal power station for a highly superheated mixture of water and steam from a depth ranging between 7 and 10 kilometers, is under serious consideration. The basic concept of this plan is to pump the surface water into the well and then lift it heated to 300-400° C by the porous masses of the earth's interior. Such a method holds promise for building in the future a power plant of up to 10 million kilowatts capacity [62].

Generation of Electric Power

Paratunka Geothermal Electric Power Station. - The Paratunka geothermal electric station is the first station in the world to operate on freon.

The Thermal Physics Institute of the Siberian Branch of the USSR Academy of Sciences, after extensive research designed a turbo-unit called Shatura HEPP-5. A prototype model of this freon unit of 340 kw was constructed and tested. Another unit, the UEF90/65, designed on the same principles, was assembled and shipped to Sredne Paratunka thermal springs for subsequent testing. After construction of the pumping station and the pipeline system, this plant was completed in September 1967. A series of tests demonstrated that this power plant operates satisfactorily using thermal water with a 81.5° C temperature, instead of the design temperature of 90° C [37].

The operating principles of this plant, schematically shown in Figure 74, are as follows: the liquid freon, preheated by the thermal water (temperature 83° C), boils and overheats to 55° C at an absolute pressure of 13.8 atmospheres in the main boiler (3) consisting of three preheaters, boilers, and superheaters. The freon steam, prehated up to 65° C, enters the radial freon-turbine (2) where it expands, reaching the required condensation pressure for the operation of the turbine. The turbine is connected to a

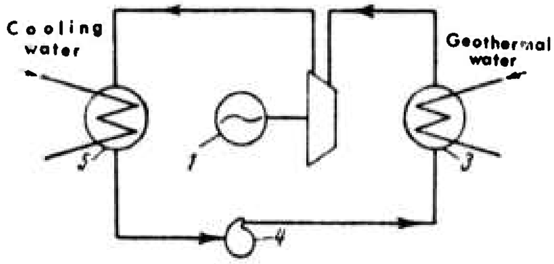

Fig. 74. Schematic of the energy cycle for the Paratunka geothermal electric station [263].

1- Generator; 2- turbine; 3- main boiler; 4- pump; 5- condenser.

T2-75-2 generator (1). From the turbine, the freon steam enters two tube-type condensers (5), where it is cooled by cold water (15° C), at an absolute pressure of 5 atmospheres. From the condensers, the liquid freon flows into the line receiver and is returned agin to the main boiler by the centrifugal pumps (4XGV-GE-40-5 model).

This plant has a receiving charge-discharge unit consisting of two receivers having a capacity of 6 cubic meters each, and two AK-FV-6 piston-type freon compressor-condenser units designed for the removal of freon from the system, the resupply of freon, and the refilling of the system with freon after installation or maintenance.

The maximum consumption of geothermal water (including water used to heat the station) is 289 cubic meters per hour while the consumption of water for cooling is 1520 cubic meters per hour. In selecting the site for a power plant, besides the existing geothermal waters, the volume of water available for cooling cycles is also of considerable importance.

The distance between the geothermal wells and the station is about 1000 meters. With the completion of the power station building in late 1964, eight geothermal wells had been finished, ranging in depth between 302 and 604 meters with the diameters ranging between 123 and 200 millimeters. At the wellhead, the thermal water attains a head of 30 meters.

The discharge of free-flow thermal water at each wellhead was registered at about 18 liters per second, and the average temperature was 83.7° C. To eliminate head decrease (about 0.55 liter per second per meter), booster-pumps were installed in order to maintain the required operating head.

To provide thermal water of the required 81 liters per second discharge, six wells are used with one well in reserve. Water for cooling is brought from the Paratunka river into the pumping station by two suction pipes; from here it is pumped through pressure pipes into the power station.

The Paratunka station consists of two units. In the main unit is the machine hall (Fig. 75), and in the annex is the control panel, machine shop,

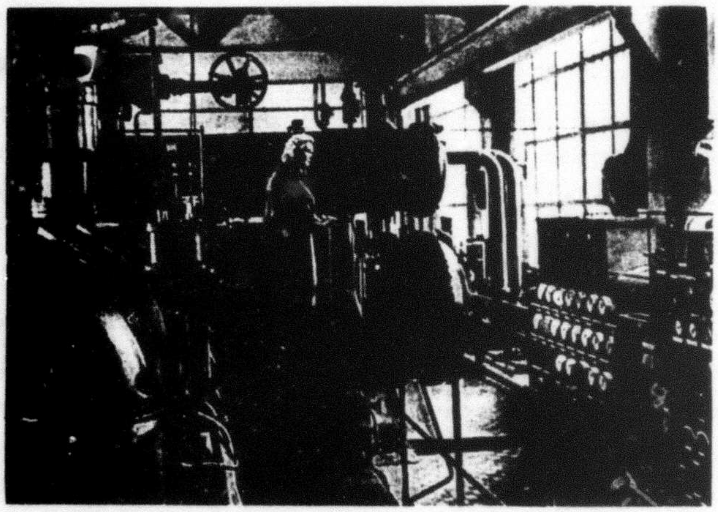

Fig. 75. The Machine hall of the Paratunka geothermal electric station [45].

chemical laboratory, equipment and mercury rooms, ventilation chamber, and utility room. For the first two years, the annex unit was used as an experimental laboratory by the Thermal Physics Institute.

The machine hall (Fig. 76) is 12 meters wide, 24 meters long, and 8 meters high, while the annex is 12x12 meters, with a height of 3.6 to 4.0 meters.

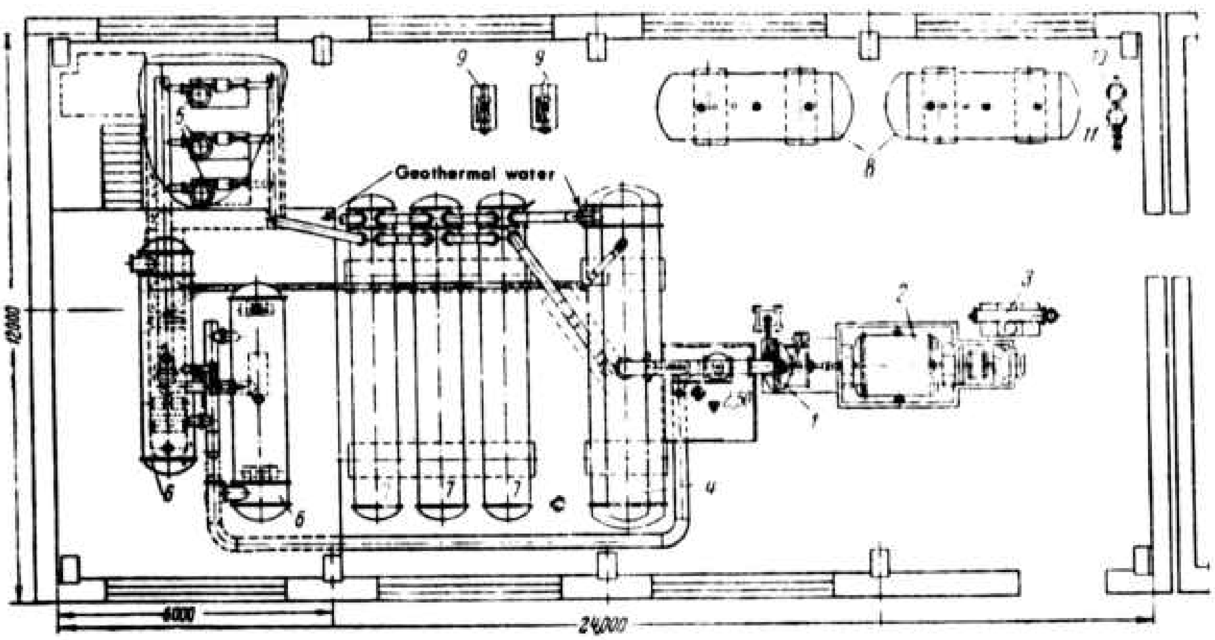

Fig. 76. Plan of the machine hall of the Paratunka geothermal electric station (dimensions in mm) [263].

1- Turbine; 2- generator with exciter; 3- generator lubrication system; 4- boiler; 5- freon pump; 6- condenser; 7- preheater; 8- freon-line receiver; 9- compressor-condenser unit; 10- freon filter; 11- freon drier.

The electric station has the following technical-economic characteristics:

- installed capacity — 750 kw*
- consumption of electric energy by the power station — 35%
- cost of 1 kw of installed capacity — 1600 rubles (1967)

* In a recent source [108], the installed capacity is given as 1000 kw.

The high cost of the installed capacity (4 times higher than that of the Pauzhetka geothermal electric power station operating on a steam-water mixture) is explained by the comparatively small capacity of the station and the excessive construction of pipes and other installations for the supply of thermal waters to neighboring hothousing-greenhousing facilities. In addition, the final cost included all expenses in connection with planning, construction and testing of the freon turbo-unit (Shatura HEPP-5) [263].

According to this same source [263], there were plans to construct a similar geothermal electric station with a 25 MW capacity near the twon of Petropavlovsk-Kamchatskiy.

Pauzhetka Geothermal Electric Power Station. - The Pauzhetka geothermal electric station (Fig. 77), located in the Pauzhetka river valley, was commissioned in July 1967.

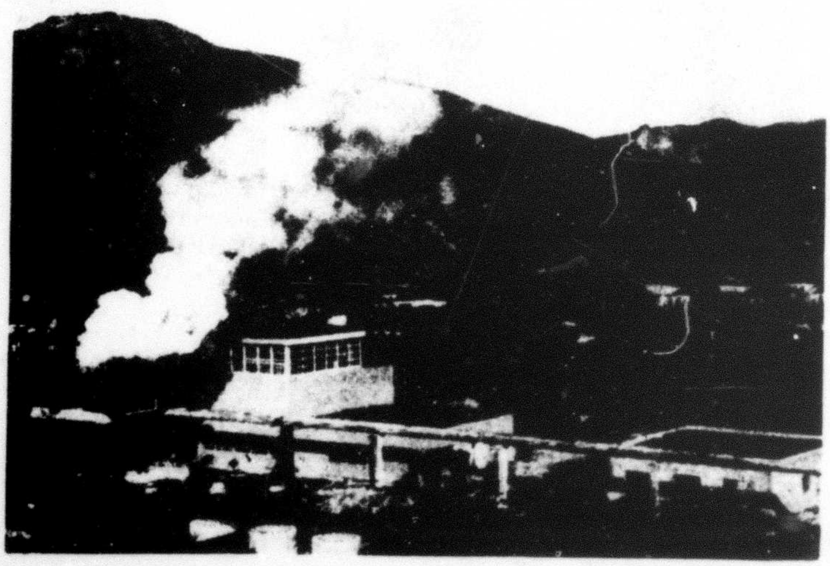

Fig. 77. Pauzhetka geothermal electric power station [33].

In the Pauzhetka river valley, during 1965, 22 wells were drilled to a maximum depth of 800 meters, the average depth being 300 meters. The highest temperature recorded at the surface was 187° C, with the average temperature at 170° C. Surface pressures ranged between 2.2 and 6.7 atmospheres, with mineralization between 3 and 3.5 grams per liter. Average discharge capacity of the hot water-steam mixture has been estimated at 170 kilograms per second [33, 45].

According to original design estimates, this station was to operate on steam-hot water mixture with a natural heat capacity of 170 kcal/kg at the surface obtainable from wells 100 to 400 meters deep, and was to have the following technical-economic indices [264, 265].

Initiating capacity	5 MW
Total discharge of wells	500 tons per hour
Hours in operation	7000 annually
Annaul production of electric energy	35 million kw/hr
Annual loss of heat	25,000 Gcal
Cost of one kw of installed capacity	400 rubles
Cost per kw/hr	0.65 kopeck
Electricity consummed by station	10%*
Efficiency factor of the station (net)	9.2%
Operating personnel	21 (10)
Staff coefficient	4 men per 1000 kw

In the first stage of construction (1966), an initiating capacity of 3 MW was to be produced by two turbines operating with a pressure of 1.2 atmospheres and utilizing seven geothermal wells. An eighth well was used for research and as a reserve well [265].

In the second stage of the construction (1967), by drilling two additional wells, a considerable increase in discharge and pressure was to be obtained. Increased pressure from 1.2 to 2.0 atmospheres consequently

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* The 1963 estimate was 1.6% [264].

was to increase the capacity of the station to 5 MW, which is the current figure for the station. Below is a schematic outline of the Pauzhetka geothermal station (Fig. 78).

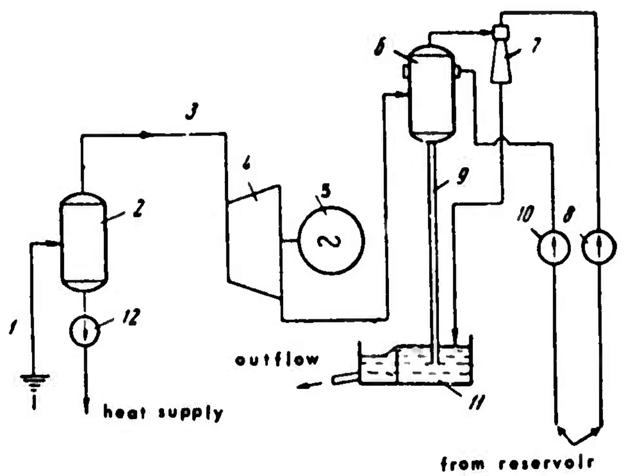

Fig. 78. Schematic of the 5 MW Pauzhetka geothermal electric power station [265].

1- Geothermal well; 2- separator; 3- steam pipe; 4- turbine; 5- generator; 6- mixing condenser; 7- water-jet ejector; 8- ejector pump; 9- barometric tube; 10- cool water pump; 11- outflow of hot water.

The third stage of construction, planned 1968, to increase the capacity of the station to 12.5 MW in 1968, did not materialize.

A schematic outline of the Pauzhetka geothermal electric power station with a planned [265] capacity of 12.5 MW is given below (Fig. 79). Besides the unfulfilled plans for expansion of this station up to 12.5 MW, there reportedly have been other, additional plans to bring this station up to a final capacity of 20 MW.

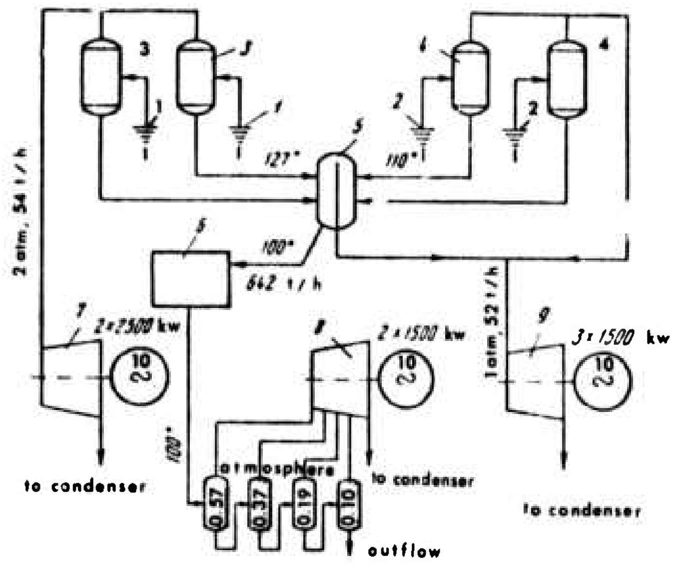

Fig. 79. Planned arrangement of the Pauzhetka geothermal electric station with a capacity of 12.5 MW [265].

1- Wells with 2.5 atm; 2- wells with 1.5 atm; 3- separators with 2.5 atm; 4- separators with 1.5 atm; 5- expander for 1 atm; 6- hot water storage tank; 7- 2 turbines (each 2500 kw at 2 atm); 8- 2 vacuum turbines (each 1500 kw); 9- 3 turbines (each 1500 kw at 1 atm); 10- generators.

The main building is 4,400 cubic meters in size and is connected to the wells by pipes having a total length of 1.3 kilometers. The machine hall floor space is 33 by 9 meters, and the control room is housed in a 4-meter-wide auxiliary building. The MK-2.5 turbines were manufactured by the Thermal Turbine Machine Construction Plant at Kaluga.

The Pauzhetka geothermal electric station supplies electricity over a 30-km-long, 35 kv power line from a 5600 kv transformer to the Ozernovsk fishing combine, the "Krasnny Truzhenik" collective farm, and the village of Pauzhetka [45].

The production costs of electricity at Pauzhetka has been estimated at 0.55 kopeck per kw/hr (1963) [264], 0.65 kopeck per kw/hr (1965) [265], and 7.2 US mills per kw/hr (1970) [266]. Considering the size of the plant and its remote location, the last figure given seems to be a very satisfactory one, and it will undoubtedly be much less when the plant is expanded. The Soviets claim that it is 30% cheaper than any alternative means of power supplied in the same area, and it has been estimated that this station will pay for itself within 3 to 4 years of operation.

Future Programs. - Besides the existing geothermal power station, there are several prospective sites for the construction of additional geothermal power stations. For instance, in the Tersko-Kumsk artesian basin (towns of Makhachkala, Khasavyurt, Kizlyar, and others) geothermal waters have been found at a depths of 2,500 - 3,000 meters, with temperatures of about 120° C and discharge capacity ranging between 1,500 and 3,000 cubic meters daily. The pressures range between 5 and 10 atmospheres, with mineralization less than 2.5 grams per liter.

There are also several regions being considered for the future construction of geothermal power stations utilizing low-temperature geothermal waters.

Additional potential sites for low-temperature geothermal power stations utilizing fissure waters are located in the northeastern USSR; i.e., the Mogoysk and Uakitsk hot springs (Buryat ASSR), and the Mechigmen, Sinyavina, and Chaplino hot springs in the Chukotskiy (Chukchi) Natsional'nyy Okrug [33].

Below are available data on several geothermal power stations planned for construction in the near future.

Bol'she-Bannaya geothermal electric power station. - The construction of this station, about 60 kilometers from the twon of Petropavlovsk-Kamchatskiy, has been under consideration since 1965. At present, only 20 geothermal wells have been drilled, with only minor construction activities under way at the site (Fig. 80).

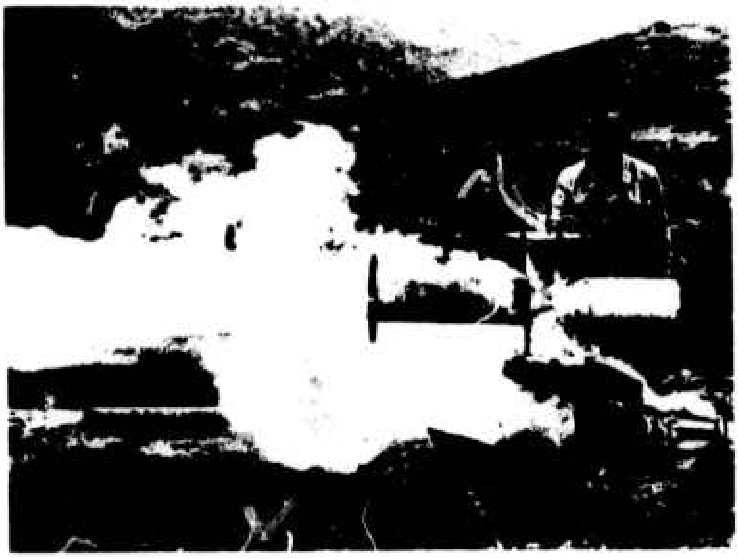

Fig. 80. High pressure steam-hot water well of the future Bol'she-Bannaya geothermal power station [265].

During exploratory work in 1965, some wells produced about 73 kilograms per second of steam-hot water mixture with an average heat capacity of 150 kcal/kg at natural discharge. With additional wells, there is a possibility of increasing the volume up to 220 kilograms per second. It is estimated that this volume will warrant the operation of an electric station with an 8 MW capacity [265].

Below is a schematic layout of the first stage for the proposed power station (Fig. 81). All wells will be directly connected to the separators (2).

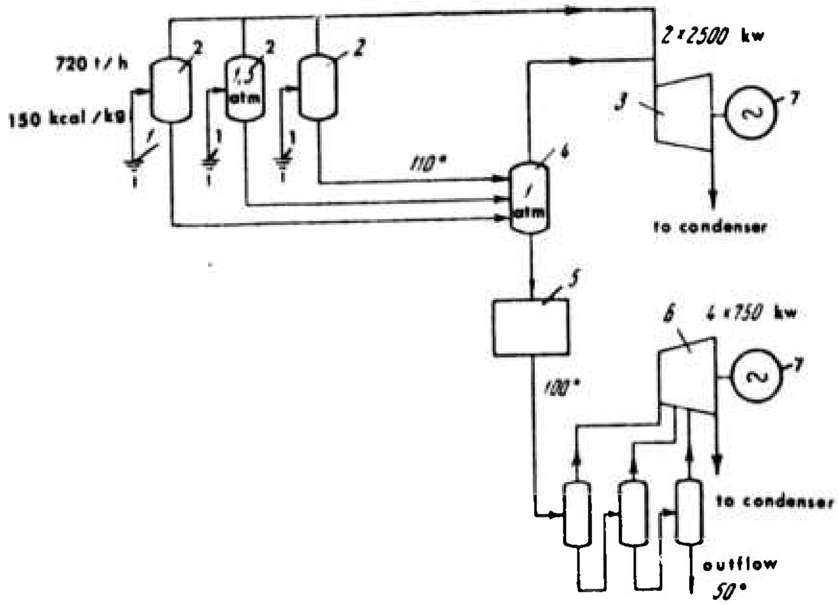

Fig. 81. Schematic of the first stage of construction of the Bol'she-Bannaya geothermal power station for 8 MW capacity [265].

1- Wells at 1.5 atm.; 2- separators at 1.5 atm.; 3- 2 turbines (each 2,500 kw at 1 atm.); 4- expander at 1 atm.; 5- hot water storage tank; 6- 4 vacuum turbines (each 750 kw); 7- generators.

Steam with pressure between 1 and 1.2 atmospheres will be channeled into the turbines (3), while the hot water will be channeled into the expander (4) in order to reach the required pressure of one atmosphere. From the expander (4), hot water (100° C) will enter the hot-water storage tanke (5) and then the vacuum turbines (6) [265].

Based n Soviet estimates, the cost of the station will be about 2.5 million rubles. The initiating capacity of 8 MW is rated as minimal, since the station will start operation with a steam-hot water mixture of only 200 kilograms per second discharge. To increase the capacity, the use of low-boiling agents (freon, isobutane, and others) are under condiseration. In this way, it is expected to increase the output by about 50%, and by operating with a steam-hot water mixture of over 200 kilograms per second discharge rate, the station will have a capacity of 12 MW. By fully utilizing the available resources (estimated at 400 kilograms per second of steam-hot water mixture), the capacity of the station eventually can be increased to 24 MW [265].

The cost of electricity is estimated at 2 to 2.5 kopecks per kw/hr, representing one-sixth to one-seventh of the prevailing cost in the city of Petropavlovsk-Kamchatskiy.

However, the existing 20 wells represent only 50% of the geothermal resources required for the operation of a station with 24 MW capacity, and additional prospecting drilling is needed to provide the necessary volume. The construction cost of this plant constitutes and additional problem, and the construction probably will not progress as planned.

Makhachkala Geothermal Electric Power Station. - This geothermal power station, designed by the Dagestan Branch of the USSR Academy of Sciences and the Design Institute of the Thermal Electric Station Planning Enterprise, in the first stage of development will have an initiating capacity of 12 MW. There are indications that this station will be expanded to yield a much larger capacity, but for the present no definite data are available regarding the exact capacity and the date of completion [45, 62]. In this region, at a depth between 2,500 and 3,000 meters, the geothermal waters attain a temperature of 120° C, with the discharge ranging between 1,500 and 3,000 cubic meters per day at a pressure of 5 to 10 atmospheres; mineralization is not more than 2.5 grams per liter. To reach geothermal waters with temperatures above 160° C, deep drilling to a depth of 4,000 to 4,500 meters has been in progress since 1965. These prospecting activities are related to Soviet plans for increasing the production capacity of this station [33]. As part of this prospecting, at Berekey, near the town of Makhachkala in the Dagestan ASSR (Fig. 73), drilling to a depth of 4,500 meters to reach the steam-hot water mixture is in progress. During the drilling, a highly mineralized steam-hot water mixture was obtained (from an undisclosed depth), with an estimated discharge capacity of 70,000 cubic meters daily, having a temperature of 57° C at the surface. The Soviets expect to tap about $94.54 \cdot 10^{10}$ kcal hot water annually, which is equivalent to 94,535 tons of fuel oil, or 107,456 tons of coal [25, 44].

The Makhachkala station is designed for geothermal water with a natural heat capacity of 160 kcal/kg at the surface, obtainable from depths ranging between 4000 and 4500 meters, to satisfy the electricity and heat requirements of the town of Makhachkala. The estimated technical-economic data for this station are summarized as follows [264]:

Total discharge of wells	100 tons per hour
Initiating capacity	12 MW
Number of hours in operation	8000 annually
Annual production of electric energy	96 million kw/hr
Annual loss of heat	100, 000 Gcal
Electricity consumed by the station	5%
Staff coefficient	2 men per 1000 kw

Yuzhno-Kuril'sk Geothermal Electric Power Station. - The Yuzhno-Kuril'sk geothermal power station on Kunashir Island (Kurile Island group), will have an initiating capacity of 5-6 MW. The station, to be erected at the Goryachiy Plyazh site about 8 kilometers from the town of Yuzhno-Kuril'sk, will operate on geothermal water at a temperature of 130° C. There are also several steam producing vents at this site, having temperatures ranging between 100 and 130° C [33].

The discharge rate of the steam-hot water mixture is not high and estimated at 1.5 kilograms per second. However, data presented by the Institute of Volcanology of the Siberian Branch of the USSR Academy of Sciences indicate that the average discharge volume is actually much larger (given as 77 kilograms per second) with a total caloric value of 36 Gcal per hour. The minimum caloric value has been estimated at 130 kcal per kilogram. In January 1965, the Sakhalin Geological Administration started several drillings at the site, but at present no additional technical data are available regarding the progress and the purpose of this activity [265].

The Goryachiy Plyazh area, abundant with geothermal surface manifestations, is being considered for exploitation for space heating, agriculture and other purposes, in addition to the generation of electric power. The Thermal Physics Institute of the Siberian Branch of the USSR Academy of Sciences presently is studying the technical-economic aspects of the construction of this station [267].

Additional future developments of considerable importance have been planned for the following sites [265].

The Verkhne-Koshelevsk fumaroles, are located about 22 kilometers southeast of the village of Ozernoye.

The Severo-Kambal'nyy fumaroles, are located about 10 - 12 kilometers from the Pauzhetka station. By preliminary estimates, the discharge volume is put at 100 tons per hour of dry steam which has high energy potential. It has been estimated that one tone of hot water at a temperature of 100° C can produce 4 kw/hr of energy, while one ton of dry steam can produce about 100 kw/hr, i.e., a 25-fold increase in output of electricity, as compared with hot water.

The Zhirovskiy geothermal springs have not been studied in detail and, consequently, their data are limited. It is estimated that the discharge rate is about 15 kilograms per second, and the steam mixture has a temperature of 100° C at the surface. During 1968-1970, some prospecting and research activities were to take place for the purpose of producing a number of wells having a total length of 19,000 meters. From these activities, it has been established that the masimum temperature ranges between 100 and 130° C, with the natural heat capacity between 25 and 60 million calories per second with a production capacity of about 36 MW.

Other Applications of Geothermal Resources. - In the USSR, hot water is found in over 20 percent of the nation, although the present explored potential amounts only to 1 percent. It has been estimated that during 1970, the total fuel cost saving arising from the use of hot geothermal waters amounted to one million dollars. By 1980, this saving is expected to be approximately 10 million dollars [34].

Besides generating electric power, geothermal energy has broad application in several fields of the national economy. There are presently many engineering projects of varying scale and purpose in various stages of completion across the USSR, and describing all of them woul be beyond the scope of this study. Therefore, only the major projects of basic interest to the respective fields will be outlined in order to illustrate the degree and magnitude of multipurpose exploitation of geothermal resources [31].

Domestic and Industrial Applications

Heating. - The largest user of geothermal energy for heating is the Soviet Union, where consumption of low-temperature waters from thermal springs or drill holes represents an annual savings of about 15 million tons of conventional fuel. A ten times greater saving is expected by 1980. It is estimated that 50 to 60 percent of the USSR territory contains thermal waters which are economically exploitable, with the total heat value being comparable with the total coal, oil and peat resources of the country [31].

Considering the annual heating demand, several Soviet scientists have investigated the possibility of using geothermal water for district heating in conjunction with fossil fuel boilers operating during peak heating months. They stress the importance of seasonal demands on the overall geothermal load factor and also indicate the limitations which apply to the direct use of cooler waters for heating. To overcome the low temperature disadvantage, the Soviets are stressing the great potential of the lithium-bromide absorption machine operated with geothermal energy as a heat pump for winter heating and air conditioning in the summer [34].

Regarding heating systems, among most interesting is that used by the town of Paratunka, Kamchatka, to heat three 48-unit apartment houses. The maximum load is 0.55 Gcal/l, and geothermal water at 80° C is used for heating both the tap water and the apratments. A conventional radiator system or radiant heating with pipes embedded in the floors or ceilings is used, and the heating system is designed for a temperature drop from 80 to 40° C. Utilizing a heat pump, part of the 40° C return water can be reheated to 60° C by extracting heat from the remainder of the return water, which in turn is cooled to 10° C. The 60° C water is mixed with the 80° C geothermal water. The temperature of this mixture can be increased as desired by an electrical peak heating unit. Increased loads during cold speels can also be met by increasing the heat extraction from the geothermal water with the heat pump [268].

Pipelining of hot water will improve the present poor heating conditions of Petropavlovsk-Kamchatskiy, where only about 30 percent of its households have individual steam heating. The town is supplied with heat from the Paratunka geothermal fields, a distance of 45 to 65 kilometers, by different means (Fig. 82).

Fig. 82. Insulated pipes for heating of Petropavlovsk-Kamchatskiy [267].

In the town of Makhachkala and adjacent areas, utilization of geothermal waters for heating of domestic and industrial space was initiated 24 years ago following the discovery of thermal waters as a result of oil prospecting. From about 100 oil wells, having depths between 1200 and 1500 meters, 40 wells produce hot water at 60 to 70° C utilized for heating about 9,000 square meters of domestic and industrial space. The capacity of the wells has been estimated at 2000 cubic meters daily, with plans being considered to increase the heating capacity to 10,000 cubic meters daily.

At the town of Groznyy, the Caucasus Special Geothermal Directorate (Ministry of Gas Industry) recently commissioned two powerful geothermal wells which will be utilized for heating of the town, replacing the present heating system operating on gas which during the winter months proved to be insufficient [267].

The largest single heating system in the USSR serves three districts of the twon of Cherkassk with about 19,000 inhabitants [268].

Presently, several towns are under consideration for heating by geothermal waters, such as Armavir, Poti, Gudermes, Nal'chik, Tyumen, Tobol'sk, Arshan, Tsaishi, Fergana, Chartak, and many others [261].

Hot Water Supply. - Hot water from geothermal springs and wells with moderate temperatures and of required chemical composition are being used extensively for domestic, industrial, and other hot-water supply. To meet required specifications, the chemical compositions of geothermal water should not exceed 1 g/l of dry residuals, 0.5 g/l of sulfate, 0.35 g/l of chloride, and 7 mg-equiv/l of average hardness. Besides the required clarity, taste, and odor, the content of heavy metal salts, radioactive elements and other contaminants should be within the established norms. In addition, the content of lead should not exceed 0.1 mg/l, while arsenic, fluorine, copper, and zinc should not exceed 0.5, 1.5, 3.0 and 5.0 mg/l, respectively.

Hot water supply syst ns are constructed using conventional techniques and equipment and, in many cases, in conjunction with heating systems [33] g/l of chloride, and 7 mg-equiv/l of average hardness. Besides the required clarity, taste, and odor, the content of heavy metal salts, radioactive elements and other contaminants should be within the established norms. In addition, the content of lead should not exceed 0.1 mg/l, while arsenic, fluorine, copper, and zinc should not exceed 0.5, 1.5, 3.0 and 5.0 mg/l, respectively [33].

Hot water supply systems are constructed using conventional techniques and equipment and, in many cases, in conjunction with heating systems.

<u>Permafrost - Mining and Construction.</u> - The Soviets foresee future large-scale use of geothermal waters in mine heating to facilitate the exploitation of mineral resources in permafrost, frozen soil, and regions subject to long and severe winters [42].

In Magadan Oblast', the main gold mining region in th Soviet Union, scientists are studying methods for year-round hydraulic placer mining with geothermal waters. Similar methods are under consideration in the mining of diamonds, lead and other minerals abundant in the Taymyr, Yakutia, Kolyma, and Chukotsk regions.

A study conducted by the Leningrad Mining Institute indicates that for this type of mining, the thermal water should have a temperature between 20 and 30° C and a minimum discharge of 250 cubic meters per hour.

There are two ways to obtain geothermal waters for the above purposes [33].

• by direct tapping of thermal waters with a temperature above 25° C, regardless of the degree of mineralization;

• by injecting cold water into deep, specially drilled wells, where it will be heated above 25° C by the deep regional geothermal (dry heat) field. It has been estimated that one such well can produce 400-500 cubic meters per hour of thermal water at 20-80° C for a duration of 10 to 30 years, i.e., the equivalent of 2-20 million kcal/h capacity.

Possibilities also exist for utilizing geothermal waters for various types of construction in permafrost and frozen soil. Applied thermal water creates a hot slurry which, through gravity, penetrates into the frozen soil and facilitates drilling of holes for pillars and other foundation components.

Refrigeration and Air Conditioning. - Geothermal waters are a very cheap source for refrigeration and air conditioning in domestic, public and industrial installations, with great savings of over hundreds of thousands kilowatts of electric energy possible. Geothermal waters with temperatures above 13° C provide better results for year-round air conditioning applications. Thermal waters of 70° C require special conversion equipment. To obtain temperatures above 0° C, special lithium-bromide machines are in use, and for temperatures below zero, the ammonia-water machines are appropriate.

Below is a schematic diagram (Fig. 83), and general view (Fig. 84), of a lithium-bromide absorption unit.

This unit was designed by the Thermophysical Institute of Siberian Branch of the USSR Academy of Sciences and was tested at the Chernigov Synthetic Fiber Plant. It operates on thermal water with a temperature ranging between 85 and 120°C. This unit has a capacity of 2.5 Gcal/hr, is manufactured in the USSR, and is in great demand for refrigeration in various chemical industries such as synthetic rubber, ammonia and at metallurgical plants. The arrangement and operation characteristics of the unit are similar to units used in other countries [43].

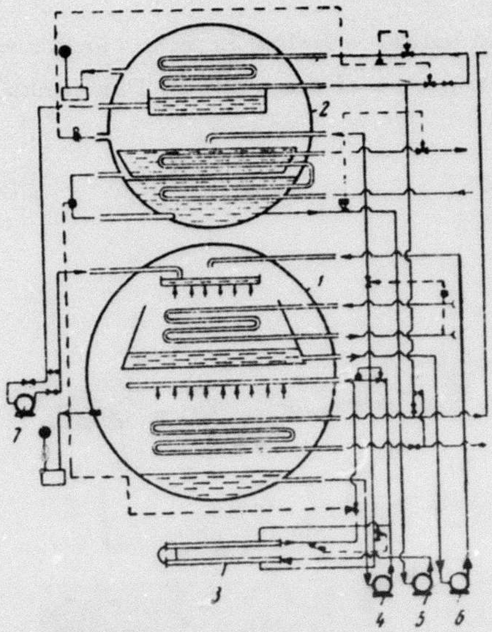

Fig. 83. Schematic of a lithium-bromide absorption unit [43].

1- Absorber-evaporator; 2- generator-condenser; 3- heat exchanger; 4-7- pumps.

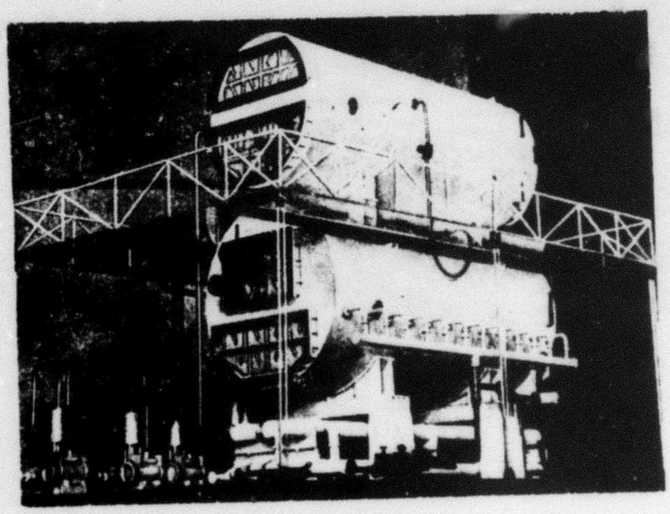

Fig. 84. General view of a lithium-bromide absorption unit [40].

Swimming pools and baths. - Below is an outdoor swimming pool utilizing geothermal water from one of the wells in Paratunka river valley (Fig. 85).

Fig. 85. Outdoor geothermal swimming pool in the Paratunka river valley [26].

Near the town of Nal'chik, there are five geothermal wells ranging in depth between 1600 and 2840 meters with a free flow discharge capacity of 9000 cubic meters daily at temperatures between 50 and 80° C, and mineralization of 0.6 to 78 grams per liter. Presently, only one well with a temperature of 80° C is supplying several swimming pools with thermal waters. The 80° C temperature is cooled to the required temperature of 25 to 40° C [269].

At present, there are many towns and resort centers utilizing thermal waters for the above purposes, and only a few have been mentioned here.

Agricultural applications. - Agricultural use of geothermal waters for hotbed and hothouse cultivation of vegetables has increased considerably in recent years. It has been estimated, that one hectare (2.47 acres) of heated soil will produce year-round vegetables for a town with a population of 10,000 and for a town of 100,000 about 10 hectares will be required. The norms for above acreage are based on standards established by the Food Institute of the USSR Academy of Medical Sciences assuming an annual per capita consumption of about 146 kilograms (400 grams daily) of the fresh vegetables grown in hotbeds or hothouses. It is desirable, that 25% of the above quota should be naturally grown vegetables [32].

In general, the water temperature varies according to the type of farming, geographic location, and season. A temperature of 60° C is required for hothousing in winter and 50° C in spring; for heated hotbeds, a temperature of 40° C is required, while for heating of soil (sheltered or unsheltered), 30° C temperatures are appropriate. The thermal water for heating of shielded soil (by glass plates, plastics, or wooden boards) should have natural heat capacity of $2.5 \cdot 10^6$ cal/hr, a temperature between 35 and 40° C, and a head of at least 10-15 meters at the surface. Heating soil by the shielding method is said to be 4 to 5 times cheaper than by hothousing installations. This method has been used in Kamchatka, Kazakhstan and the Caucasus foreland, and has proven to be very economical [33].

The temperature of water used for heating soil and for thermal irrigation should be above 25° C. For thermal irrigation, the mineralization should not exceed 2 grams per liter.

In 1970, it was reported [33], that the largest hothousing complex in the world, at Sredne-Paratunka springs, was being completed and would cover an area of 60,000 square meters. Production in the initial stage is expected to be 900 to 1000 tons of fresh vegetables annually and the final production goal is set at 2000 tons annually.

Another hothousing complex in the planning stage is in the Pauzhetka thermal springs region, which will cover an area of 150,000 square meters and will have an estimated annual production capacity of 1800 tons of fresh vegetables.

Near the twon of Makhachkala there are several hothousing complexes (Fig. 86) with moderate production capacity. However, to increase the supply

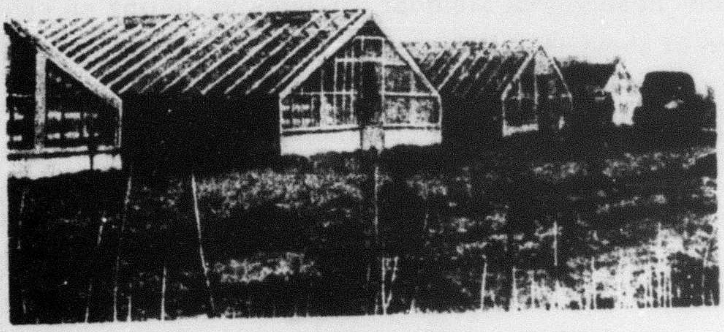

Fig. 86. Hothousing complex near the town of Makhachkala [45].

of fresh vegetables to the town of Makhachkala and adjacent areas, several hothousing projects are in the planning stages or nearing completion (Fig. 87).

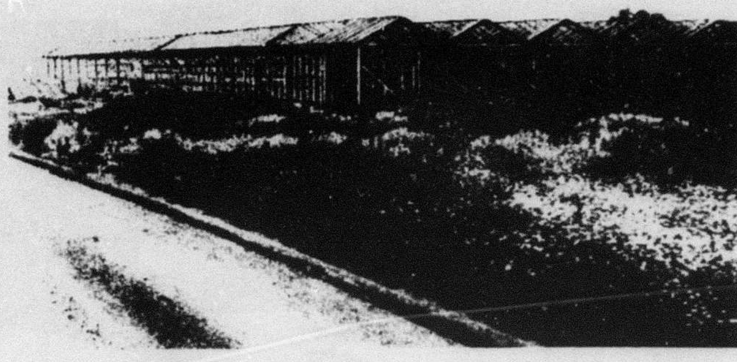

Fig. 87. Hothousing project (near completion) in the vicinity of Makhachkala [33].

It has been estimated that the production capacity of hothousing complexes in this area will amount 3000 tons annually. Also in the planning stages, are several hothousing projects near the towns of Khasavyurt, Groznyy, Stavropol', and Tobol'sk [33].

At Kislovodsk, Stavropol' district, a new greenhouse complex (Fig. 88) having an area of 120,000 m^2, produces year-round fresh vegetable for towns of northern Caucasus. From 1 m^2 they produce 29 kg of cucumbers or 11 kg of tomatoes [272].

Agricultural use of geothermal water is being considered also in Sakhalin Oblast', especially in the Kurile Islands, the Yakutsk ASSR, and Magadan Oblast', where the Soviets appear to be confronted with the immediate problem of a geothermal resources survey. On the other hand, in Lorino and vicinity (Magadan Oblast') geothermal resources are already being utilized for hothousing, but on a rather moderate scale.

Fig. 88. Greenhouse complex at Kislovodsk [272].

Medical and healt applications. - Over the years, thermal water has been used by clinics, hospitals, and health resorts in many countries for therapeutic purposes.*

Out of 1500 hot water springs in the Soviet Union, over 340 are utilized exclusively by sanatoriums, hospitals, and health resorts. In addition, there are 86 mineral water bottling plants presently in operation [270].

Based on medical research and empirical experience, geothermal waters and their chemical components have a significant healing influence on various human maladies. The basic indicators for the therapeutic value of thermal waters are: mineralization, ion content, gas saturation, gaseous

* The first health resort in Russia was established in 1714, in Karelia.

components, content of specific biologically active components (CO_2, H_2S, As, Fe, Br, I, H_2SiO_3), radioactivity (Rn), hydrogen ion concentration (pH), and water temperature. To be considered for balneological use, the thermal water should meet the following norms: overall mineralization 2 g/l, content of soluble CO_2 - 0.5 g/l (for external application, 1.4 g/l), content of H_2S - 10 mg/l, As - 0.7 mg/l, Fe - 20 mg/l, Br - 25 mg/l, I - 5 mg/l, H_2SiO_3 - 50 mg/l, and Rn - 5 mμ Curie/l. However, the above stated content of As, Fe, Br and I pertain to therapeutic drinking water with an overall mineralization of 10 g/l [33].

Various therapeutic treatment and health resort facilities using low-temperature springs have been developed in the Soviet Union, especially in the Soviet Far East. The largest balneological resort center, near the town of Nal'chik, utilizes one geothermal well having a temperature of 80°C [269].

In the bed of dry Duzkan lake, (Fig. 89), near the town of Chardzhou (Turkmen SSR) there are many thermal water holes utilized by the local people for balenological treatment [271].

Fig. 89. Thermal water holes in the bed of dry Duzkan Lake [271].

Considerable therapeutic value has been attributed to the Garm-Chashma thermal springs (Fig. 90) in the Anderob river valley near the town of Khorog (Tadzhik SSR). Several years ago, a balneological sanatorium was built, with an additional two presently in the planning stage.

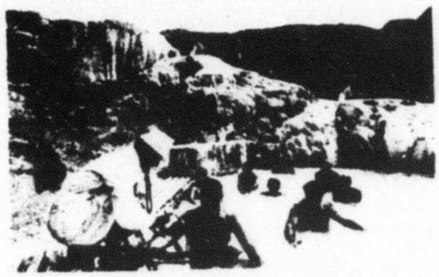

Fig. 90. The Garm-Chasma thermal spring near the town of Khorog [271].

The hot springs area in the southern part of Kamchatka Oblast' has developed considerably with modern facilities for medical treatment and recuperation. There are sanatoriums with good medical treatment facilities at Nachiki and Paratunka.

Recently, several hot spring areas have been developed for medical treatment, such as:

Magadan Oblast'. The Talaya hot springs have a well-equipped sanatorium, and the recently discovered Novoye Chaplino hot springs are in the development stage for medical treatment. Hot springs near the town of Lorino are being used for medical treatment and recuperation.

Sakhalin Oblast'. Hot springs have been discovered sporadically on the main island. For instance, at the town of Sinegorsk there is a large medical treatment facility, and the hot springs in the vicinity of Dagi have been utilized as health resorts.

However, several hot spring areas are in the planning stage for development in the near future as balneological, medical and health centers [85]. Geothermal waters with their therapeutic potentials have been regarded as very valuable to the national economy and to the population's health.

The Hydrogeological and Hydrophysical Institute of the Kazakh Academy of Sciences recently published a comprehensive study emphasizing the curative value of geothermal and mineral waters. The study indicates that therapeutically valuable elements, such as radon, iron, hydrogen sulfide, and iodine-bromine have been found in thermal waters of southern Kazakhstan, in the Mangyshlak peninsula, and the Sary-Arki desert [63].

The Ministry of the Food Industry, in cooperation with the Central Scientific Research Institute for Balneology and Physiotherapy (Ministry of Health) is accelerating the production of bottled mineral waters. It has been estimated that the production capacity is over 1.5 billion bottles annually. During the five-year plan (1971-1975) several large bottling plants are to be built and production is to be increased by about 2.4 times. One plant under consideration will have a capacity of 250 million bottles annually.

About 80% of the resources presently being utilized are located in the northern Caucasus, the Ukraine, and Transcaucasia. A considerable increase in bottling has been achieved in Soviet Central Asia, Chita and Kemerovo Oblast's, and Kamchatka peninsula. Presently, about 80 new mineral water sources are recommended for immediate exploitation.

<u>Geothermal by-products</u>. - Geothermal waters are enriched with about 80 different chemical elements, which can be extracted either coincident to the purification processes of thermal waters intended for geothermal electric power stations and other facilities, or specifically for the chemical industry [33, 44].

The extraction of sodium and magnesium sulfates, iodine, and bromide from geothermal waters has been carried out in the Soviet Union. For example, in the Kashkadar'insk artesian basin (Uzbek SSR) from only one exploratory well, about 2,700 tons of salts (mostly potassium chloride), 9 tons of bromine, and about 100 kilograms of iodine have been extracted in one year [45, 46].

Recently, the Soviets announced that techniques for the extraction of boron, alkali and alkali-earth metals, and trace elements are being developed [46].

Frequently, hot and superheated geothermal waters contain large amounts of salt, iodine, bromine, naphthenic acid (mixture of cycloparaffin acids), boron, strontium, lithium, fluorine, and other rare elements, which can be extracted easily for the chemical industry [44].

The potential benefits from extracting chemical elements from highly mineralized geothermal waters can be demonstrated with actual data as follows:

- Near the town of Berekey, Dagestan ASSR, during prospecting drilling, well no. 3 (Fig. 73) produced a fountain of high mineralized water (brine) with a discharge capacity of 70,000 cubic meters daily. Considering the discharge volume and the amount of chemical elements, it has been calculated that in one year such a well could produce [44]:

Elements	Tons
$NaCl$	1,470,000
KCl	30,000
$CaCl_2$	30,000
$BaCl_2$	14,300
$MgCl_2$	24,300
$SrCl_2$	277
various trace elements	6,704
Total :	1,575,581 tons

• During prospecting drilling in the oil region of Datykh, Chechen-Ingush ASSR, well no. 6 produced a highly mineralized water (brine) fountain having a discharge capacity of 40,000 cubic meters daily. It has been calculated that annually, this well can produce [44]:

Elements	Tons
$NaCl$	636,690
$CaCl_2$	78,930
$MgCl_2$	80,000
$MgSo_4$	4,000
various trace elements	2,240
Total :	802,370 tons

The geothermal waters of the Cheleken peninsula annually produce about 300 to 360 tons of lead, 48 to 50 tons of zinc, 24 to 35 tons of copper, and several other components valuable for chemical industry.

The western Siberian and Irkutsk basins are prospective sites for the extraction of iodine, bromine, and several other elements. In addition, the Kamchatka peninsula and the Kurile Islands are considered as potential regions for the extraction of bromine, rubidium, cesium, lithium and arsenic from available superheated water and steam [33].

Near the town of Zhigalovo , Irkutsk Oblas', during prospecting drilling, a well 1125 meters deep produced highly mineralized geothermal water with brine density of 0.4 g/cm^3 and the soluble salts at 600 grams per liter. This high content of salts represents a very valuable raw material for the various chemical products for which eastern Siberia has a great need. However, the exploitation of these valuable minerals is still in the early stage, and considerable work has to be done to achieve production on an industrial scale [44].

In conclusion, a long period of scientific investigations and engineering planning and experimenting is now developing on a large scale exploitation of geothermal energy.

The geothermal development in the USSR went along original patterns, largely different from the other countries. Investigations on the heat flow and deep thermal processes have been carried out for a long time in the whole territory of the USSR. Geothermal maps covering the entire territory have been prepared as a summary of the very abundant information gathered from all sources, like oil and water wells, mines, scientific investigations and so on. This information is obtained as a routine work by the geological service.

On the basis of these widespread investigations, a very important and somewhat surprising conclusion is offered: today it is known that 50-60% of the territory of the USSR is occupied by thermal waters which are available to the economic applications. They are commensurable with the coal, oil, gas and peat resources taken together. The potential resources of thermal waters in the wide regions are estimated by enormous figures. The previous calculations of the thermal water reserve at a depth of 1000-3500 m from the surface having the temperatures 50-130^{o} C are estimated by $7.9 \cdot 10^{6}$ m^{3} for twenty four hours. A considerable part (about 70%) of the thermal water debit mentioned above falls on the depth up to 1500 m from the surface.

These statements summarize several decades of geothermal investigations in the USSR. The papers presented by the USSR scientists offer a new philosophy on geothermal energy. The main points are:

- Geothermal energy is a common natural resource like hydroelectric energy, coal and oil.

- Geothermal energy is not limited to the volcanic areas; many sedimentary basins offer commercial geothermal resources.

- The utilization of the hot waters with a temperature above 50° C is competitive with the fossil fuels in space conditioning, and in many other fields, like agriculture (greenhouses, hydroponics, frozen foods) and mining.

- Geothermal energy may change the economy of the circumpolar areas (Siberia, North Canada, Alaska).

- Hot water below and near boiling point can generate electric power at a competitive cost.

Many geothermal projects have been realized and more are under way. The geothermal energy exploitation in the USSR is carried out by stages. The first stage is of course the evaluation of the geothermal possibilities by drilling. The second step is an economical feasibility study on geothermal energy utilization. Power generation, space heating, agricultural and industrial uses are considered and a geothermal project for the area is prepared. It requires an engineering development, which is carried out by a technological organization. The appropriate industrial designs are prepared, a pilot plant is tested and the machinery is manufactured and put into experimental operation. If successful, the same technique is used in other projects. There is a very close collaboration between the scientific organizations, first of all the USSR Academy of Sciences, and the industrial operators.

At present, 11 geothermal projects are in operation in the USSR, that the total amount of heat produced is 200 Gcal/h, or about the equivalent of 125,000 tons of conventional fossil fuel. An increase of at least 10 times the amount is envisaged for the period 1970-1980.

A large development program for the utilization of hot water in space heating and agriculture is under way. In the volcanic areas, the economical advantages of geothermal power generation have been proven by some experimental projects and the development of the production is under consideration in accord with the growing local energy demand.

B. Conclusion

Ten years ago, the geothermal energy exploitation was centered mainly on power production. The success of geothermal space and greenhouse heating in Iceland started many similar projects in several other countries.

The pioneering work carried out in the USSR, U.S., Japan, New Zealand and other countries gives evidence that water below boiling point may be a competitive source of energy for space conditioning, greenhouses and hot ground projects, poultry and fish farming, mining and other industrial projects, industrial refrigeration and fresh water production.

Geothermal energy is a very common source of energy and the techniques for its exploration and exploitation have been developed. No major technological problem has been revealed in the projects under operation at present.

Hot water in the temperature range of 50-100°C can be utilized as a cheap source of energy in many fields. Its exploitation does not require a large amount of capital and the delay intime for its utilization is short.

Many countries are carrying on more or less basic or advanced exploration and exploitation programs, especially for space heating and greenhousing. In these countries reasonable data, catalogues and maps of the surface manifestation, as well as feasibility studies are at various stages of preparation. Geological and geochemical data are also provided. Apart from the high scientific value of such investigations, these countries are gathering the basic geothermal information for a commercial development.

The following presents a brief outline of geothermal research and

developments in various countries:

A pioneering geothermal development was begun in the 1950s at Kibukwe, in Katanga province of Zaire (Congo), where a 220-KW geothermal generating plant was installed at a metal mine. This plant, which used wet steam at about 95°, was costly and inefficient, but served satisfactorily for many years in a remote area far from cheap alternative power supplies. The plant and mine are now shut down.

In February 1972 it was reported that a small, experimental power station had operated successfully at Tengwu, in Kwangtung Province of the People's Republic of China. The station is reported to use steam flashed from hot water to turn turbines, but no details are available on plant size, water temperature, or operating characteristics.

In 1967 the United States undertook a project of geothermal exploration for the Government of Nicaragua, utilizing private U.S. concerns as contractors. Detailed geophysical surveys and geochemical and geologic evaluations were made, and a series of temperature-gradient holes was drilled in fumarolic terrain near Momotambo volcano in west-central Nicaragua. A deeper drill-hole encountered temperatures to 230°, but the project was allowed to lapse. In 1972 the United Nations entered into an agreement with the Government of Nicaragua for a second phase of exploration, which is now under way.

At Melun, France, about 50 km southeast of Paris, two holes drilled to depths of 1,800 m intersect an artesian aquifer with water at approximately 70°. Nonetheless, a district-heating scheme is being evaluated in which one well would be used for production and the other for reinjection of heat-depleted water. Heat energy produced from this scheme would be offered at prices competitive with other fuels. The artesian basin is believed to be quite vast.

Many other countries of southern and eastern Europe, Latin America, north Africa, and Asia have begun the collection of data for geothermal exploration. Prominent among them are Algeria, Colombia,

Greece, Guatemala, India, Israel, Spain (Canary Islands), Venezuela, and Yugoslavia. In general, there are over 50 countries active or interested in geothermal exploration and development.

Temperature-gradient drilling in northeastern Algeria has outlined a region of anomalous gradient near the Tunisian border. Detailed geological and geochemical studies suggest a buried batholithic mass as the source of heat for the numerous hot springs of the region.

The Government of Guatemala has chosen a geothermal area near Moyuta volcano, near the border with El Salvador, for detailed exploration. Consideration is being given to contracting in 1972 for a deep exploration hole, and several engineering firms have been asked to submit proposals for a drilling and development program.

The Spanish government is supporting geothermal exploration in the Canary Islands, a Spanish territory off the coast of Morocco. Very-high-temperature fumaroles are reported at Lanzarote Island.

In Yugoslavia and Czechoslovakia, temperature-gradient and heat-flow studies are currently in progress, with an eye to locating sizable reserves of low-enthalpy fluids for use in space heating, agriculture, and industry.

In six underdeveloped nations (El Salvador, Chile, Turkey, Kenya, Ethiopia, and Nicaragua) the United Nations has sponsored geothermal exploration jointly with the national governments. United Nations missions have also been made to India, Greece, Peru, and Guatemala in the recent years to evaluate potentials for exploration; cooperative exploration projects have been proposed in several cases. The United States has supported exploration in Nicaragua and Indonesia through the Agency for International Development. Colonial administrations have carried out exploration in such underdeveloped places as the Territory of Afars and Issas (French Somaliland), the Fiji Islands, and New Britian.

Private concerns have assisted in geothermal exploration in the Philipines, Algeria, Guadeloupe, and elsewhere. Usually, the initial stages of data collection and the preparation of geologic-reconnaissance reports, power demand projections, and transmission grid maps, are undertaken by the local geological survey or electricity agency. Shallow borings are often made at this stage, too. Much of the exploration to date has been financed and carried out by agencies of the countries involved, for in many cases the geothermal resources are owned nationally and are thus not at the disposal of private landowners. But because many nations lack a sophisticated geological infrastructure, detailed exploration is likely to require cooperative ventures with the United Nations, with more developed nations, or with private concerns.

In Hungary the consumption of hot water for space heating may more than double through the rest of this decade. Hot water heating schemes may become operational in Yugoslavia, Czechoslovakia, France, and elsewhere in Europe by then.

Small plants are likely to be operating or under construction in the Philippines, Kenya, Chile, Turkey, and Taiwan by 1980, and perhaps in Guadeloupe, Nicaragua, and elsewhere. Their aggregate output is likely to be between 70 and 150 MW. But because of the 4 or 5 year minimum lead time required for exploration and construction, it is unlikely that extensive plant construction will have been undertaken elsewhere by 1980; conceivably, another 50 MW of generating facilities will be erected in, for example, Indonesia, Ethiopia.

Thus, a conservative projection of worldwide geothermal generating capacity by 1980 is on the order of 2,500 MW, or three times present-day capacity. Because world consumption of electricity during this 4-year period is likely to double, the geothermal power component of world output will remain at less than 1 percent of total generating capacity. Direct utilization of geothermal energy is likely to increase at a faster rate, especially in eastern Europe.

More rapid development is foreseen in the 1980s. It will depend in part upon improvements in geothermal drilling and utilization technology, increased knowledge of geothermal systems, and greater availability of funds for geothermal exploration and development [10].

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